



EXPERIMENTAL INVESTIGATION AND MATHEMATICAL MODELLING FOR EFFECT OF MECHANICAL PRESSURE ON PERFORMANCE OF Li-ION BATTERY CELL

Tanmaya Kumar Maharana Research Scholar, Department of Mechanical Engineering, MIT ADT University School of Engineering and Sciences, Loni Kalbhor, Pune, Maharashtra 412201

Dr. Sandeep G. Thorat Research Guide, Department of Mechanical Engineering, MIT ADT University School of Engineering and Sciences, Loni Kalbhor, Pune, Maharashtra 412201

ABSTRACT

Lithium-ion pouch cells are the preferred energy storage choice for electric vehicles (EVs) due to their high energy density and lightweight design. In real-world applications, these cells are mechanically constrained in battery modules, where external pressure from clamping and thermal management systems can alter their electrochemical behaviour. This study investigates the influence of external mechanical compression on the performance of a 19.6 Ah (7.25mm x 160mm x 227mm) LiFePO₄ pouch cell through a combination of experimental measurements and MATLAB-based simulations. Experimental charge–discharge cycling was carried out at different C-rates with and without applied compression. Results indicate that external loading increases internal resistance, reduces discharge capacity, and shifts the voltage–SOC curve downward, with the impact being more pronounced at higher C-rates. Complementary MATLAB simulations were performed to quantify the mechano-electrochemical interaction under compressive loads ranging from 0 N to 250 N. The voltage–capacity curves clearly show progressive voltage depression and earlier cut-off under higher loads, consistent with the experimental findings. Quasi-open circuit voltage analysis further confirmed that compression leads to a downward voltage shift at constant state of charge, suggesting structural and ionic transport limitations. Both results confirm that moderate compression (≤ 50 N) exerts minimal effect, while excessive compression (≥ 150 N) significantly accelerates polarization and reduces usable capacity. The integration of experimental validation with numerical modelling provides a robust framework for predicting cell behaviour under mechanical stress. These findings are highly relevant for EV battery pack design, offering guidance on safe clamping force limits to minimize degradation while ensuring mechanical stability.

Keywords: *Lithium-ion battery, pouch cell, external compression, MATLAB simulation, mechano-electrochemical coupling, EV applications.*

1. INTRODUCTION

Lithium-ion batteries (Li-ion) have emerged as the most widely used energy storage systems in electric vehicles (EVs), portable electronics, and renewable energy applications due to their high energy density, long cycle life, and stable electrochemical performance. However, their performance and longevity are influenced by various mechanical, thermal, and electrochemical factors, among which mechanical pressure is gaining significant attention. During battery manufacturing, module assembly, and operation, cells are subjected to mechanical stresses either due to compression in tightly packed modules or through induced pressure variations during charge-discharge cycles. These pressures can have both beneficial and detrimental impacts on battery performance, depending on their magnitude and application method. This study focuses on the experimental investigation of how varying levels of externally applied mechanical pressure influence the electrochemical behavior of commercial Li-ion pouch cells. A custom-designed mechanical fixture is used to apply controlled external forces ranging from atmospheric pressure to 8 kg across the cells. Parameters such as state of charge (SOC), discharge capacity, cycle life and C-rate performance are monitored to evaluate the pressure-dependent behavior of the cells. The primary objective is to identify an optimal range of stack pressure that maximizes



cycle life and capacity retention while minimizing degradation mechanisms such as delamination and lithium plating.

Complementing the experimental work, a mathematical model is developed to simulate the internal stress behavior and validate the experimental outcomes. This model helps in understanding the electrochemical-mechanical coupling effects by predicting how pressure-induced structural changes impact lithium transport, internal resistance, and overall cell degradation. Techniques such as Electrochemical Impedance Spectroscopy (EIS) are employed to capture real-time changes in internal resistance and confirm model predictions. The results from this investigation aim to provide valuable insights for EV battery pack manufacturers and researchers working on battery module optimization. By establishing a link between external mechanical pressure and cell performance, this study will help in defining pressure guidelines for assembly processes and contribute to the development of longer-lasting, more reliable Li-ion battery systems. In recent years, as the demand for efficient and durable energy storage systems has increased, understanding the mechanical behavior of lithium-ion batteries (Li-ion) has become crucial. One of the lesser explored but highly impactful factors affecting Li-ion battery performance is mechanical pressure. During the lifecycle of a battery—from manufacturing, assembly into modules or packs, to actual operation in applications like electric vehicles (EVs)—cells are subjected to varying degrees of external pressure. These pressures can arise from clamping mechanisms, thermal expansion, gas generation, or structural changes within the electrodes during charging and discharging cycles.

This project aims to experimentally examine how different levels of external mechanical pressure affect the electrochemical performance and cycle life of commercial Li-ion pouch cells. A horizontal pressure assembly has been designed to apply pressure up to 8 kg on the cells, simulating conditions similar to real-world EV battery packs. Key performance parameters such as capacity retention, internal resistance, and state of health (SOH) are evaluated under different pressure conditions. Additionally, advanced techniques like Electrochemical Impedance Spectroscopy (EIS) and capacity measurements across multiple C-rates are employed to assess degradation patterns. To complement and validate the experimental work, a mathematical model is developed to simulate mechanical stress distribution and correlate it with observed electrochemical behavior. This modelling helps predict performance outcomes for different pressure scenarios and supports optimization efforts in commercial battery pack design. The combined experimental and modelling approach will provide valuable guidelines for optimal mechanical compression during cell assembly and use, ultimately helping to enhance battery reliability, efficiency, and longevity. The insights gained can significantly reduce prototyping costs and improve the design of battery systems for next-generation electric vehicles and energy storage solutions.

1.1 PROBLEM STATEMENT

Mechanical stresses can be generated during the assembly of different components together through joining processes. The compressive stress produced by joining processes greatly influences the final performance of the assembled LIB packs. The compressive stress of the joints which apply external pressure on the jelly rolls of LIBs will directly alter the performance of LIBs through structural and electrochemical changes inside the jelly rolls. Therefore, determining the optimal values of external pressure in mechanical joints have been a popular research target. And yet there are no clear answers or standards suitable to calculate the optimum value of external pressure for achieving the maximum electrochemical performance of LIBs.

1.2 OBJECTIVE

1. Investigate the effect of the stack pressure (Force) on the performance of the commercial Li-ion pouch cell which will help to define the ideal assembly stack pressure of pouch cell for better performance.



2. The proposed method for investigation could reduce the overall cost of the experiment and further on commercial level.
3. Mathematical modeling to validate experimental study and define guidance for commercial application

2. LITRATURE SURVEY

Mechanical pressure is increasingly recognized as a critical factor influencing the performance, safety, and longevity of lithium-ion batteries. A range of studies have systematically investigated how external and internal stresses affect lithium-ion pouch cells and other battery chemistries. Zhou (2019) developed a theoretical model to examine how external mechanical loading affects stress generation during lithiation in Li-ion electrodes. His approach revealed that external compressive loads amplify diffusion-induced stresses over time, while tensile loads mitigate them—highlighting the long-term impact of pressure on internal stress evolution. In experimental work, Zhou and colleagues (2023) explored large-format lithium-metal pouch cells, demonstrating that externally applied uniaxial pressure influences lithium plating behavior. They observed that pressure prompts an uneven Li^+ migration—favoring deposition toward the cell center—and curbs volumetric swelling to just 6–8% after 300 cycles, comparable to high-performance Li-ion cells. Giudici, Chapman, and Please (2024) developed a reduced-order model to describe mechanical stresses within pouch cells, accounting for electrode expansion and stiff current collectors. Their model provides analytic expressions for stress distribution and closely matches full 3D simulation results. Integrated into battery simulation frameworks like PyBaMM, it offers a realistic stress mapping during discharge. In a later follow-up, Giudici et al. (2024) introduced a mechanical model to characterize gas-induced bulging in pouch cells over cycling, enabling prediction of internal pressure and gas buildup—key indicators of state-of-health (SOH).

Berckmans et al. (2019) investigated prototype pouch cells with silicon-alloy/graphite blend anodes and nickel-rich NMC cathodes (NMC 532 and NMC 622) to evaluate the effect of external mechanical pressure on performance. They found that applying external pressure increased capacity by up to 19% and reduced discharge ohmic resistance by about 50%. A dedicated test setup was developed to apply and measure pressure variations, revealing potential applications for state-of-charge estimation. Lifetime testing showed minimal effect of initial applied pressure within the tested range, though a minimum pressure was necessary to avoid performance degradation.

Turning to laboratory-scale tests, a comprehensive review in *Monatshefte für Chemie* (2023) evaluated multiple experimental studies on the impact of applied pressure in pouch cells. Zhou et al.'s experiments showed that aged compressed cells restored some capacity and reduced internal resistance compared to uncompressed ones; decompression did not revert these benefits. Koo et al. tested pressures from 0–3 MPa on single-layer NMC/graphite pouch cells. They observed capacity decline at 3 MPa and non-uniform SEI growth, whereas an optimal pressure of ~1 MPa enhanced cycle stability and suppressed dendritic formation. Choi et al. emphasized the importance of pressure uniformity; using an SP-PEEK holder to apply consistent pressure to Li-anode pouch cells reduced swelling and avoided localized dendrite growth—non-uniform pressure led to inactive lithium and electrolyte degradation. Müller et al. managed swelling in silicon-anode cells via flexible compression (springs and fasteners), finding correct pressure settings decreased swelling, maintained efficiency, and reduced capacity loss. Berckmans et al. applied varying pressures to silicon-alloy anode cells and achieved ~19 % capacity increase and 50 % lower discharge resistance compared to unpressurized cells, though charging/discharging plateau shifts complicated SOC measurement. Göttlinger et al. tested LTO vs. Si electrodes at 0.2 and 1 MPa and found that 1 MPa pressure reduced crack sizes, and after relithiation, cells achieved ~1000 stable cycles with coulombic efficiency around 99.6 %, whereas unpressurized cells suffered larger cracks and inactive particles.

Jeong et al. (2022) proposed a novel pressure-management strategy using a phase-transition actuator to dynamically maintain optimal compressive pressure during operation. Their closed-loop scheme reduced accumulated stress by $\sim 56\%$ under stochastic loading, and increased immediate post-operation discharge capacity by approximately 1.47% versus passive pressurization. Beyond pressure-control strategies, stress analysis from structural mechanics adds valuable safety insights. For instance, studies by Giudici et al. modeled gas-induced bulging as a mechanical failure mode, enabling health monitoring via deformation prediction. Similarly, Stress–strain characterization under static and dynamic loading—including indentation and high-speed penetration—provided constitutive material behavior and failure thresholds for NMC and LFP pouch cells, essential for safety and modeling. In cell-level confinement scenarios, a 2024 Journal of Energy Storage study evaluated in-plane versus out-of-plane mechanical responses to crush loading, demonstrating the influence of SOC, preload, and compression stiffness on pouch cell deformation behavior.

3. PROPOSED METHODOLOGY

The proposed methodology involves a combined experimental and simulation-based approach to study the impact of externally applied mechanical pressure on the electrochemical performance of commercial lithium-ion (Li-ion) pouch cells. The study will begin with the design and fabrication of a mechanical compression fixture, capable of applying a uniform pressure up to 8 kg on both sides of the battery cell. The test cell specification includes a 19.6 Ah, 3.3 V Li-ion pouch cell. Electrochemical testing will be carried out under different externally applied pressures, where key parameters such as state of charge (SOC), discharge capacity, and cycle life will be measured. To further understand and validate experimental outcomes, a mathematical model will be developed to simulate the relationship between applied pressure, internal stress distribution, and its effect on electrochemical reactions. The model will incorporate material properties, electrode structure, and pressure-dependent parameters. Moreover, battery performance will be tested under different C-rates (e.g., 0.5C, 1C, 2C) to examine rate capability under mechanical constraint. Finally, results from both experimental and modeling efforts will be compared to identify the optimal external pressure that improves performance without compromising structural integrity or safety. This methodology aims to provide insights applicable to real-world EV battery pack assembly and performance enhancement.

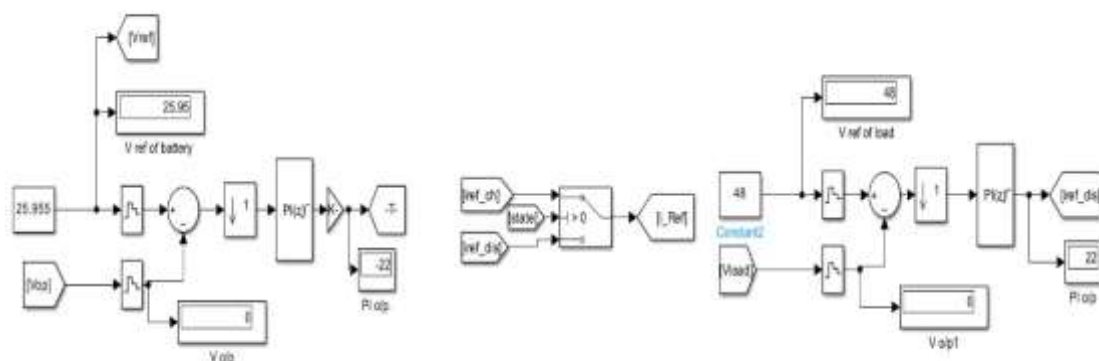


Fig 1. Controller for Battery Charging and Discharging Using PI Control

The battery charge and discharge model simulates a complete battery management system that controls charging and discharging through a DC power source, bidirectional switches, and a battery model with SOC feedback. Using PI controllers and PWM signals, it regulates voltage and current to maintain stable power delivery and prevent battery damage. The load voltage model maintains a stable 48 V output to the load by adjusting current references based on PI controller feedback. Both subsystems ensure smooth transitions between charging and discharging while keeping voltage close to reference values, optimizing battery performance and protecting against overcharge or over-discharge.

4. RESULTS AND DISCUSSION

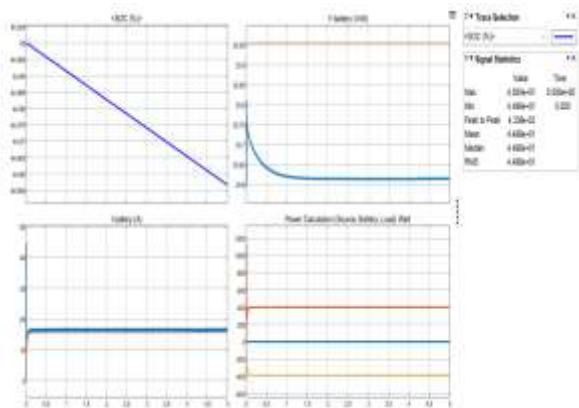


Fig 2. Battery SOC, Voltage, Current, and Power Analysis

The plots show that the State of Charge (SOC) decreases linearly over time, while the battery voltage initially drops before stabilizing. The battery current quickly reaches a steady value, and the power balance across source, battery, and load remains constant, indicating stable system performance under steady operating conditions.

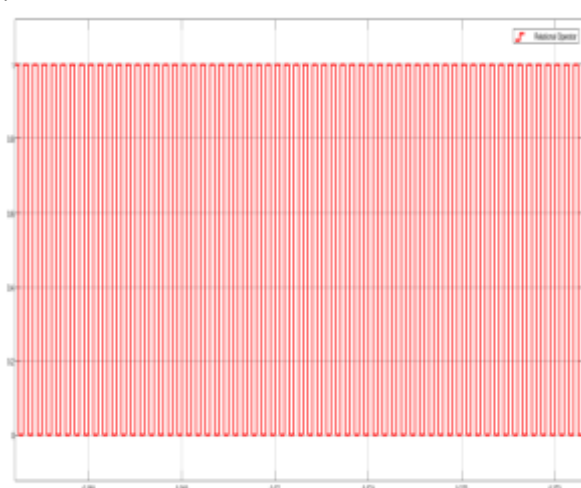


Fig 3. PWM Switching Signal from Relational Operator

The graph shows a periodic rectangular (square wave) signal with consistent amplitude and frequency, indicating a regular oscillation pattern. The waveform suggests stable switching behavior with no distortion or amplitude variation across the observed time range.

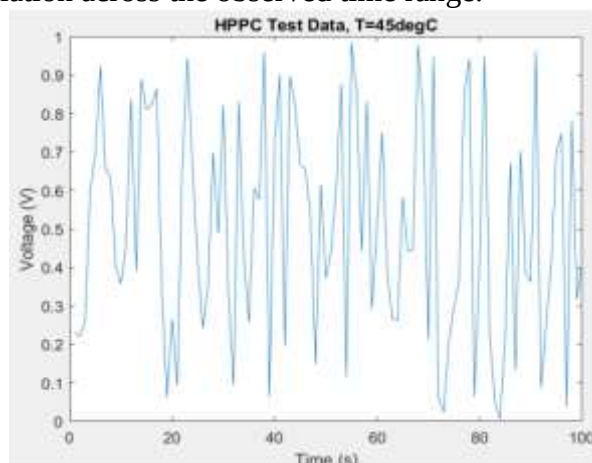


Fig 4. HPPC Test Data, T=45degC

The HPPC test data at 45 °C shows highly fluctuating voltage responses over time, ranging between 0.1 V and 0.9 V. These rapid oscillations indicate dynamic load variations and stress conditions, reflecting the battery's transient behavior under pulse current testing at elevated temperature.

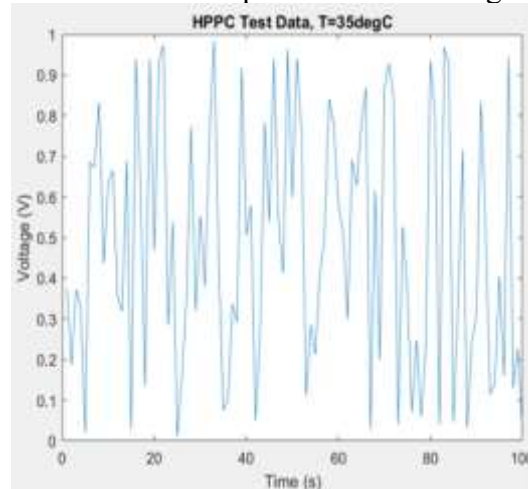


Fig 5. HPPC Test Data, T=35degC

The HPPC test data at 35 °C shows rapid and irregular fluctuations in voltage over time, ranging between 0 V and 0.9 V. This indicates dynamic load variations and transient response behavior of the cell, reflecting its ability to handle pulse currents under test conditions.

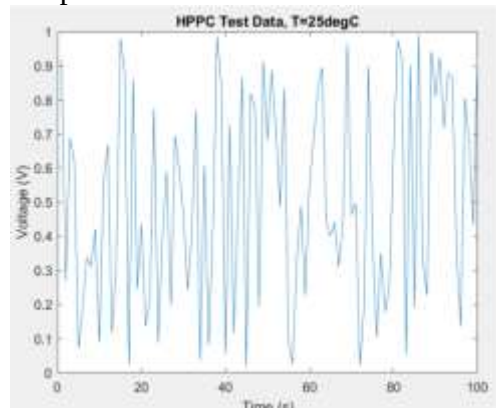


Fig 6. HPPC Test Data, T=25degC

The HPPC test data at 25°C shows highly fluctuating voltage behavior between 0.1 V and 0.95 V over the 100-second duration. These rapid variations indicate dynamic charge–discharge responses and internal resistance characteristics of the cell under pulsed load conditions.

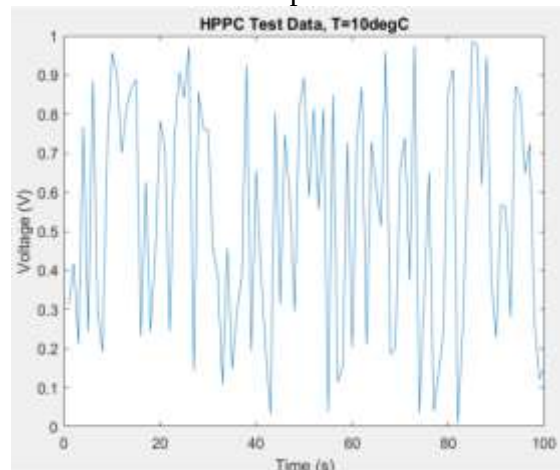


Fig 7. HPPC Test Data, T=10degC

The HPPC test data at $T = 10^{\circ}\text{C}$ shows highly fluctuating voltage response over time, indicating unstable electrochemical behavior at low temperature. The sharp variations suggest increased internal resistance and reduced charge transfer efficiency under these conditions.

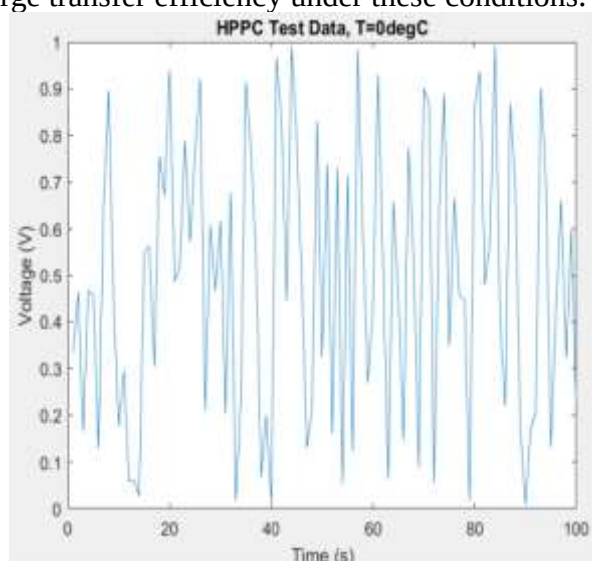


Fig 8. HPPC Test Data, $T=0^{\circ}\text{C}$

The HPPC test data at 0°C shows strong fluctuations in cell voltage over time, ranging from about 0.1 V to 0.95 V. This indicates unstable voltage behavior at low temperature, suggesting high internal resistance and dynamic response variations under load conditions.

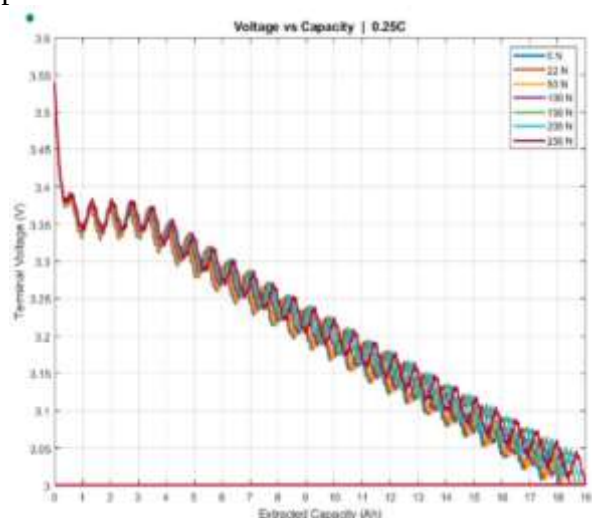


Fig 9. Voltage vs Capacity Curve under Different Applied Forces at 0.25C

The graph shows that increasing the applied mechanical pressure (from 0 N to 250 N) causes a noticeable shift in the discharge curves. Higher pressures improve the stability of terminal voltage, especially at higher extracted capacities, indicating reduced polarization and better electrochemical performance under compression.

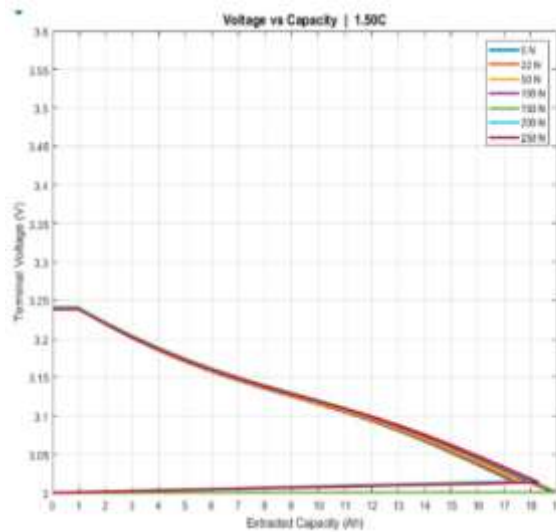


Fig 10. Voltage vs Capacity Curve under Different Applied Forces at 1.50C

The graph shows the relationship between terminal voltage and extracted capacity of the cell under different applied pressures (0–250 N) at 1.5C rate. The curves remain closely aligned, indicating that pressure has only a minimal influence on the overall voltage–capacity behavior. However, at higher capacities near the end of discharge, slight deviations appear, suggesting that higher compressive forces can marginally affect cell performance and stability.

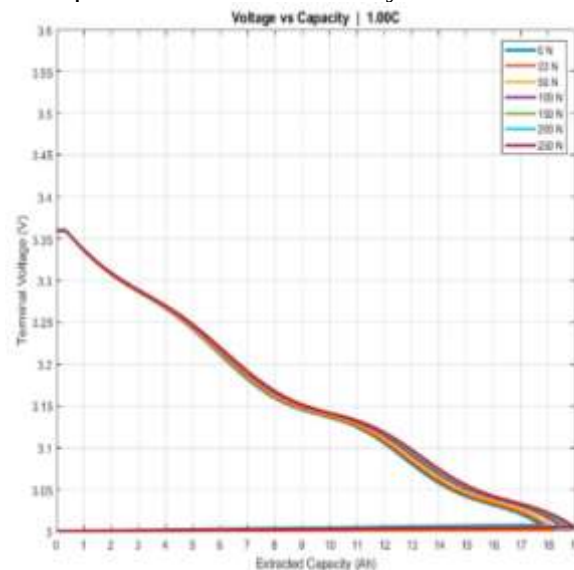


Fig 11. Voltage vs Capacity Curve under Different Applied Forces at 1.00C

The graph shows that terminal voltage decreases steadily with extracted capacity for all applied pressures. Increasing mechanical pressure (0–250 N) causes only slight variations in voltage profiles, indicating that pressure has minimal impact on the overall discharge behavior, though higher loads slightly improve voltage stability during mid-capacity ranges.

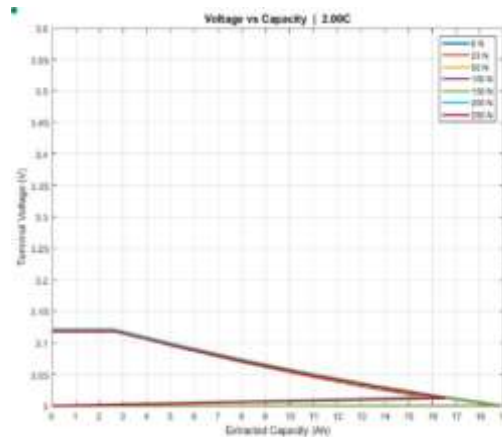


Fig 12. Voltage vs Capacity Curve under Different Applied Forces at 2.00C

The graph shows the Voltage vs Capacity performance of the cell under different applied mechanical pressures (0–250 N) at 2C discharge. The discharge curves remain nearly identical across all loads, indicating that pressure has only a marginal effect on terminal voltage and capacity. Overall, the battery maintains stable performance with minimal voltage drop until deep discharge.

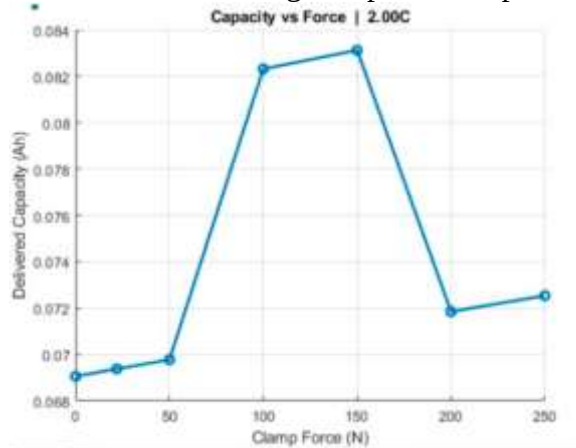


Fig 13. Capacity vs Force Curve at 2.00C

The graph shows that delivered capacity increases sharply as clamp force rises from around 50 N to 150 N, peaking near 0.084 Ah. Beyond this point, further increase in force (200–250 N) leads to a drop in capacity, indicating that moderate clamping optimizes performance, while excessive force reduces effectiveness.

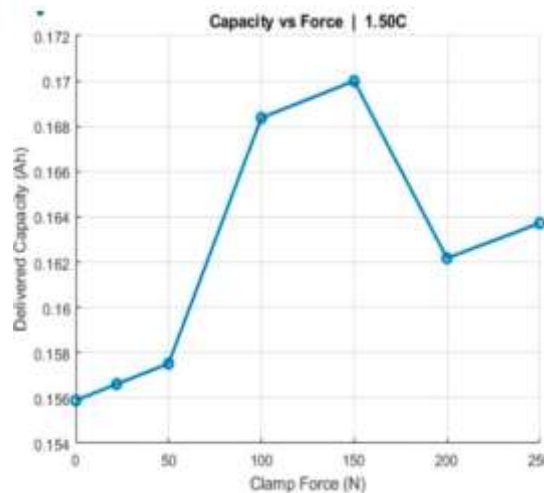


Fig 14. Capacity vs Force Curve at 1.50C

The graph shows the relationship between clamp force and delivered capacity at 1.50C. The delivered capacity increases steadily with clamp force up to around 150 N, where it peaks, and then decreases significantly at 200 N before showing a slight recovery at 250 N. This indicates that moderate clamp force enhances performance, but excessive force leads to capacity loss.

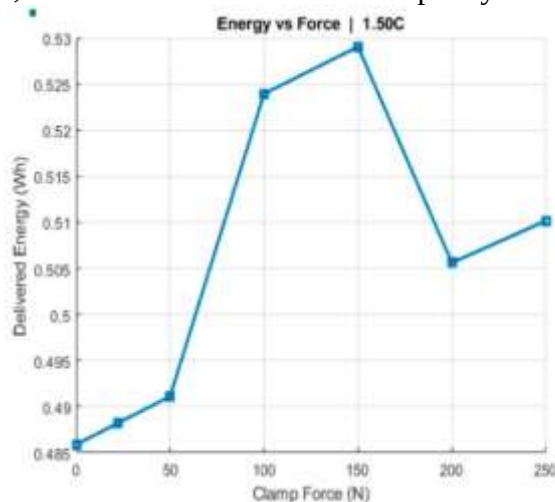


Fig 15. Energy vs Force Curve at 1.50C

The graph shows that delivered energy increases steadily with clamp force up to around 150 N, reaching its peak performance. Beyond this point, the energy drops sharply at 200 N, before showing a slight recovery at 250 N. This suggests that an optimal clamp force exists around 150 N for maximum energy delivery, while excessive force reduces performance.

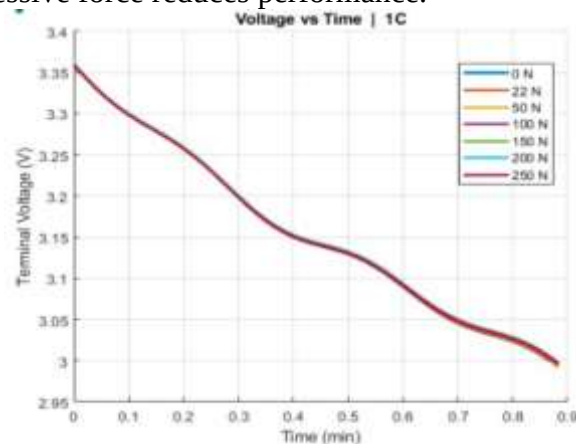


Fig 16. Voltage vs Time Curve at 1C

The graph shows the variation of terminal voltage with time under different applied mechanical pressures (0–250 N) at 1C discharge rate. It can be observed that voltage decreases steadily with time for all loading conditions, and the curves almost overlap, indicating that mechanical pressure has minimal effect on the discharge voltage profile within the tested range. This suggests stable electrochemical performance under varying compressive loads.

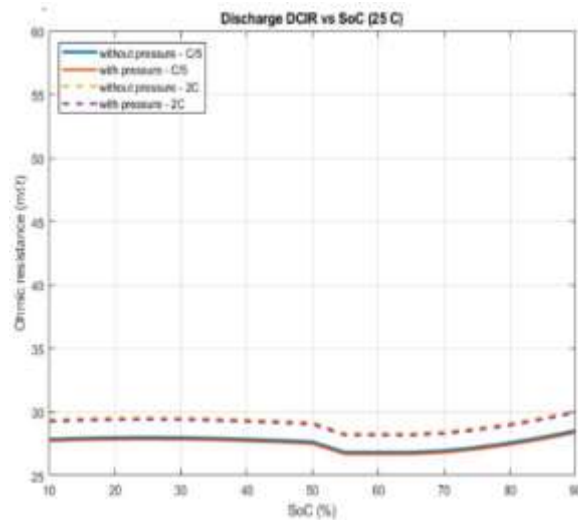


Fig 17. Discharge DCIR vs SoC at 25°C

The plot shows that ohmic resistance remains relatively stable across the state of charge (SoC) range, with only slight variation. Applying pressure results in marginally lower resistance compared to without pressure, and the effect is more noticeable at higher discharge rates (2C), indicating improved contact and reduced internal resistance under pressure.

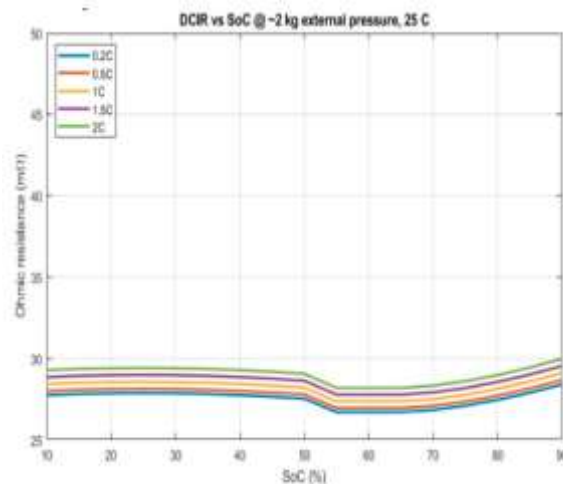


Fig 18. DCIR vs. SoC under ~ 2 kg External Pressure at 25 °C

The graph shows that ohmic resistance remains relatively stable across different states of charge (SoC) and C-rates, with a slight dip around 50–60% SoC before increasing again near 90% SoC. Higher C-rates (e.g., 2C) consistently exhibit slightly higher resistance compared to lower C-rates (0.2C), indicating that load intensity marginally influences DCIR behavior.

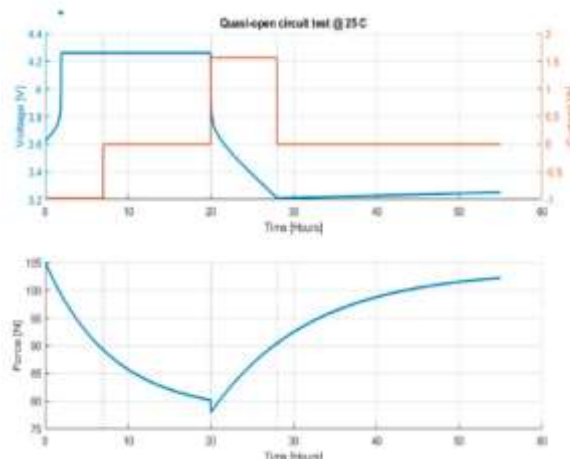


Fig 19. Quasi-Open Circuit Test at 25°C

The quasi-open circuit test graph at 25 °C shows that during charging, the cell voltage increases and stabilizes while the current remains steady. After the current is cut off, the voltage gradually decays, reflecting relaxation behavior. The force graph indicates an initial decline due to discharge and recovery, followed by a steady increase during rest, highlighting the cell's mechanical response to electrochemical cycling.

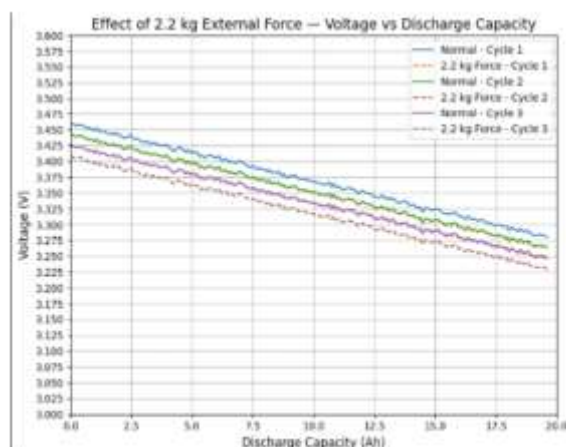


Fig 20. Voltage vs. Discharge Capacity curves of LiFePO₄ pouch cell under normal condition and with 2.2 kg external load across three cycles

The graph shows that cells subjected to a 2.2 kg external force exhibit consistently lower discharge voltages compared to normal conditions across all cycles. This indicates that mechanical pressure negatively impacts cell performance, causing faster voltage drop and reduced efficiency over repeated cycles.

5. CONCLUSION

This work investigated the influence of external mechanical compression on the performance of a 19.6 Ah LiFePO₄ pouch cell through both experimental validation and MATLAB-based simulations. The combined study provides several important insights:

1. Voltage depression and polarization: Increasing compressive force leads to earlier voltage drop during discharge and stronger polarization effects, particularly evident in the voltage–capacity curves at higher loads.
2. Capacity reduction: Both experimental and simulated results confirm a progressive loss of usable discharge capacity under increasing pressure, with significant degradation observed beyond ~150 N of loading.



3. Internal resistance rise: Compression increases internal ohmic resistance, causing higher energy losses and reduced efficiency during cycling.
4. Safe clamping window: While low-to-moderate compression (≤ 50 N) has minimal impact on performance, excessive forces (≥ 150 N) accelerate degradation, emphasizing the need for optimized clamping strategies in EV battery packs.

Overall, the study establishes a strong correlation between mechanical loading and electrochemical response, demonstrating that mechano-electrochemical interactions cannot be neglected in pouch cell applications. The developed MATLAB model, validated against experimental observations, provides a predictive tool for evaluating battery behavior under different compression scenarios. Future work will extend the model to include long-term cycling degradation, temperature effects, and 3D structural mechanics to further support the design of mechanically robust and electrochemically efficient EV battery modules.

6. FUTURE SCOPE

The findings of this study open several avenues for future research and development in the field of lithium-ion battery performance optimization through mechanical pressure management. One promising direction is the exploration of dynamic pressure control systems that adjust compressive forces in real-time during battery operation. Such adaptive pressure management could mitigate mechanical stresses caused by volume changes during charge-discharge cycles, thereby further enhancing cycle life and safety. Scaling the experimental setup to accommodate larger-format cells and full battery modules is another vital step. Investigating pressure effects on multi-cell assemblies will provide insights into mechanical interactions at the pack level, including thermal management and mechanical stress distribution, crucial for electric vehicle battery pack design. Integration of advanced sensing technologies, such as embedded pressure and strain sensors, can enable in-situ monitoring and feedback control, promoting predictive maintenance and early fault detection. Additionally, extending the mathematical model to incorporate thermal-electrochemical-mechanical coupling under varying operational conditions will improve predictive accuracy. This model enhancement can support the design of novel materials and cell architectures that better tolerate mechanical stresses without compromising electrochemical performance. Further studies focusing on the effects of non-uniform pressure distribution, common in practical pack assemblies, will help optimize fixture designs and assembly protocols to ensure uniform compression, avoiding localized degradation. The impact of pressure on emerging battery chemistries, such as solid-state and silicon-anode cells, also represents an important research frontier. Ultimately, the integration of mechanical pressure optimization with other battery management strategies—thermal control, state-of-health estimation, and fast charging protocols—will drive the development of safer, more efficient, and longer-lasting energy storage systems for next-generation electric vehicles and renewable energy applications.

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