MINISTERUL EDUCAȚIEI
UNIVERSITATEA TEHNICĂ
DIN CLUJ-NAPOCA

Field: Mechanical Engineering

PhD Thesis
– ABSTRACT –

Structural Integrity Assessment of Electric Vehicle Batteries

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Introduction and Objective of the Study:

Li-ion batteries used in electric vehicles represent an essential component both from an energy and overall safety standpoint. In the context of road accidents or during handling, they may suffer significant physical damage, which can lead to the initiation of internal short circuits, with the associated risk of spontaneous fires or explosions due to the onset of thermal runaway. Therefore, the structural safety of battery packs becomes a critical research objective for the electric vehicle industry.

This work aims to evaluate the impact resistance of Li-ion batteries by combining advanced numerical simulations in LS-DYNA software with experimental tests carried out under controlled laboratory conditions. The research integrates several fundamental stages: characterization of the battery component materials, CAD geometric modeling of the battery module, definition of relevant impact scenarios, and execution of numerical simulations focused on deformation, energy absorption, and structural integrity. These results are then validated through physical experiments, and the obtained data are comparatively analyzed to confirm the correlation between simulations and real measurements.

The study is conducted at three distinct levels: individual cell, cell pack, and complete vehicle. The work results in the creation of detailed FEM models—useful for analyzing cell component behavior during deformation—and homogenized, computationally efficient models suitable for large-scale simulations. Structural optimization solutions are proposed for battery packs and large electric vehicle batteries, to increase the level of protection during collisions. Methodologies are also proposed for defining a dynamic loading case with parameters obtained from simulating a complete electric vehicle.

Contributions:

The work is structured into four main chapters of personal contribution, each addressing an essential stage in the analysis of the mechanical behavior of Li-ion batteries.

The first chapter, dedicated to the **current state of research**, provides an overview of the progress made in the structural evaluation of batteries, highlighting the main risks associated with mechanical loads and their impact on the safety of energy storage systems.

At the cell level, detailed FEM models allow for the prediction of critical deformations and internal short circuits. The numerical modeling of Li-Ion batteries has become an indispensable tool for researchers and engineers, enabling detailed investigation of the mechanical behavior of batteries under impact conditions. The developed numerical models must be capable of capturing strain rate dependency, and the efficient use of computational resources is a major challenge.

At the pack level, studies have focused on analyzing the structure and the global loads that occur between cells, highlighting the importance of the packing layout (cell layout) in energy absorption and load distribution. Simulations at this level provide a more realistic view of the mechanical interaction between cells in compression or impact scenarios.

At the electric vehicle level, numerical research aims to integrate the battery pack into the overall vehicle body structure. Thus, energy absorption structures are investigated, as well as the efficient placement of the pack within the vehicle architecture, in order to reduce the risk of mechanical damage to the cells and to maintain the structural integrity of the vehicle in the event of accidents. These simulations contribute to the development of robust design solutions and to the topological optimization of the battery housing space.

In the second chapter, titled ***Numerical Modeling of Batteries. Calibration of Material Models***, the methods and strategies used to construct and validate numerical models capable of accurately reproducing the mechanical behavior of Li-ion cells under impact are presented. The research conducted in this phase led to the development of FEM models for cells, ranging from detailed—useful for analyzing the deformation of internal components and the potential for internal short circuits—to homogenized models, optimized for computational efficiency in simulations at the pack or vehicle level. These models were calibrated using experimental data obtained from tests on individual cell components (case, current collectors, separator) as well as on the complete cell or Jelly Roll, ensuring as accurate a correlation as possible between simulated and real behavior. The contributions of this study can be summarized as follows:

- Modeling and calibration of numerical materials using the finite element method based on experimental tests, both for individual cell components and for the entire cell, for a homogenized material approach.

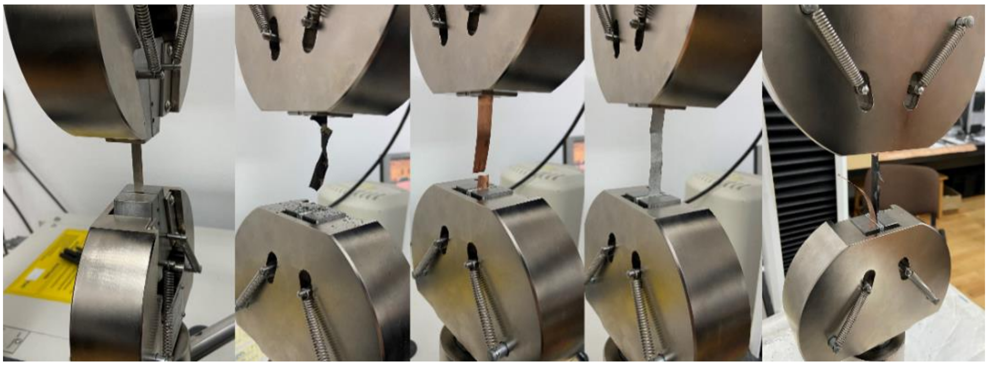


Figure 1. *Tensile testing of battery materials as individual specimens or arranged in a sandwich configuration.*

Figure 2. *Uniaxial compression test of the battery performed on a universal testing machine.*

- Validation of these materials using experimental loading cases with advanced measurement techniques, such as 3D scanning.

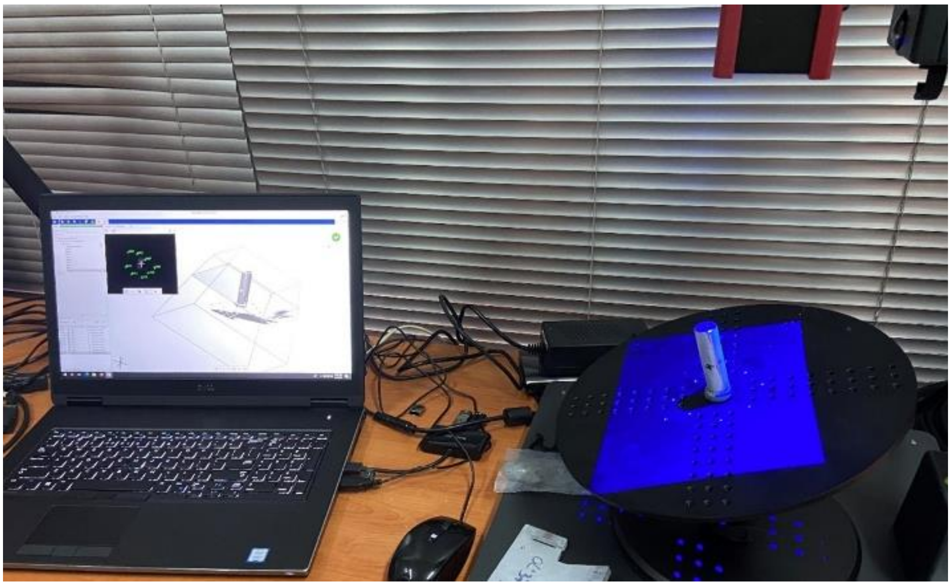


Figure 3. *Optical 3D scanning procedure of the damaged battery.*

- As a result of the material definitions, three types of numerical cell modeling were created: detailed, partially homogenized, and fully homogenized.

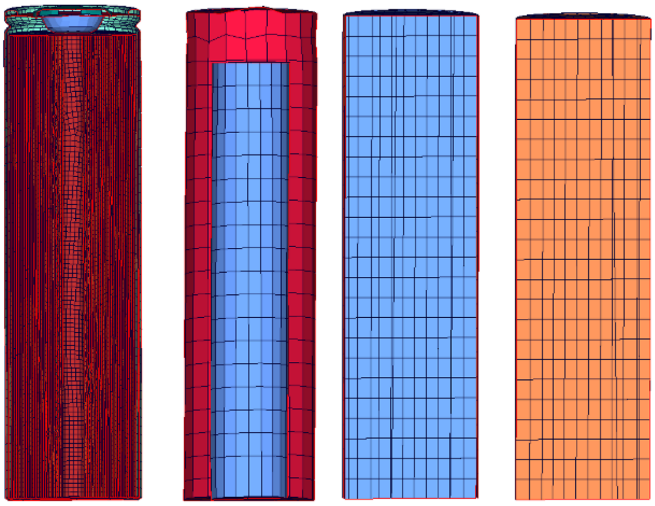


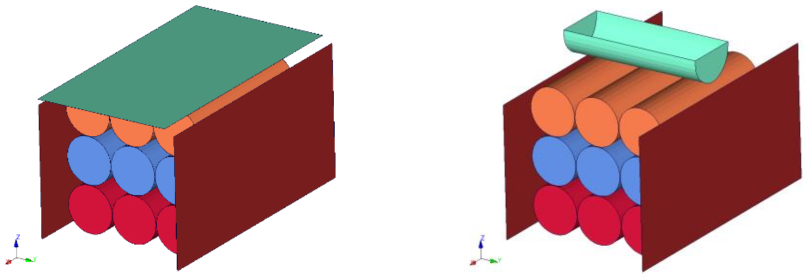
Figure 4. *From left to right, from detailed model to fully homogenized model.*

The chapter ***Mechanical Integrity Analysis of Batteries under Various Load Situations*** explores the structural behavior of battery packs subjected to various mechanical load scenarios. Based on literature documentation, an innovative constructive solution was proposed to improve structural integrity—introducing spacers between individual cells. The results highlighted the versatility of the proposed solution, particularly through: testing several cell arrangement modes within the pack, analyzing the structural behavior under different loading scenarios, both static and dynamic, and evaluating various candidate materials for the spacers. The numerical model was validated by correlating it with experimental data obtained in the laboratory, which confirmed the accuracy of the homogenized model from the previous chapter. An important aspect of the proposed solution is that improving structural resistance does not involve sacrificing the battery's energy capacity, making it ideal for implementation in real automotive applications. The contributions of this study resulted in the following:

- Finding a solution to optimize the passive safety of a Li-ion battery pack by increasing the force required for deformation. The central idea was the addition of spacers between the batteries, made from different materials: aluminum and 3D-printed PLA. Without reducing the battery volume within the pack, the required force was increased by up to four times in some cases, and intrusion was significantly reduced in dynamic impact scenarios.
- Validation of the concept through both finite element simulations and experimental testing. The good alignment between simulations and experiments strengthened the validity of the homogenized material calibrations for the individual cell. Simulation enabled the study of various loading cases: compression with a plate or cylinder, different packing configurations, or the use of different materials, to demonstrate the robustness of the proposed solution.

(**a**) (**b**)

Figure 5. *Cell pack compression experiment: (a) without spacers; (b) with printed spacers.*



(**a**) (**b**)

Figure 6. *Compression impactors used: (a) compression plate; (b) compression cylinder.*

- Comparison of experimental results with simulation data revealed a strong correlation between the force–displacement curves. In the case of the pack without spacers, the alignment was nearly perfect, while for the configuration with spacers, the experimental deformation was lower than the simulated one at a 20 kN load, indicating that the simulation underestimates the actual stiffness by approximately 20%.

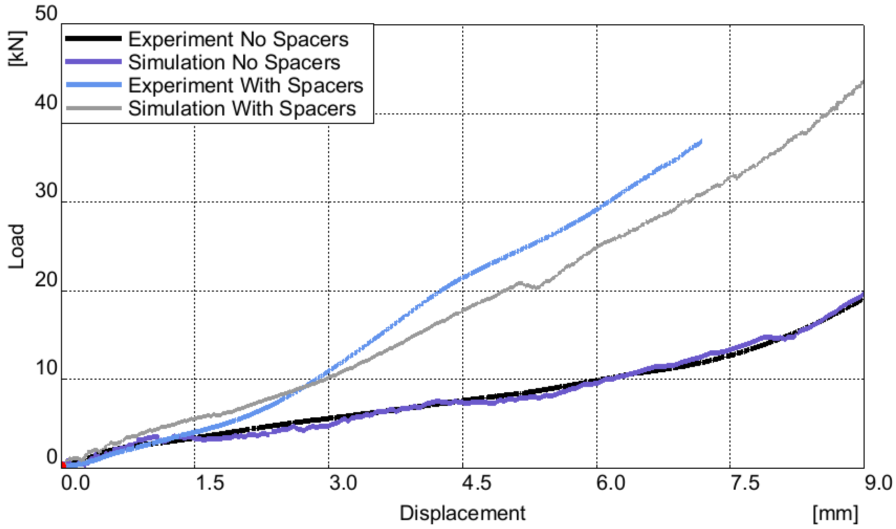
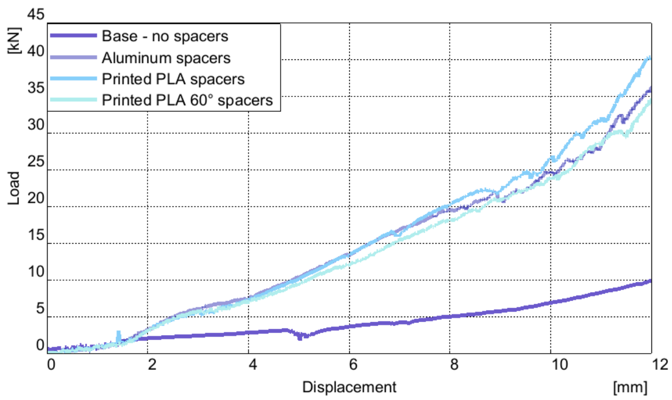
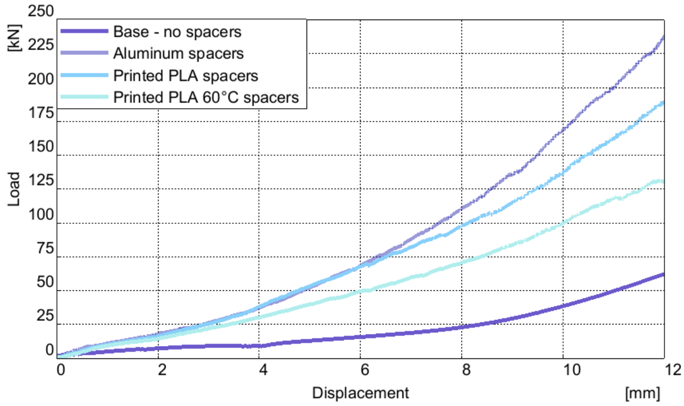


Figure 7. *Compression force–displacement validation curves.*

- Three types of materials were investigated: aluminum, 3D-printed PLA, and PLA printed and conditioned at 60 °C. It was observed that the efficiency of the spacers increases with the material's stiffness, with aluminum spacers distributing forces most effectively. Additionally, the impact on the pack's weight was evaluated, with aluminum spacers adding 26% additional mass compared to only 8% in the case of PLA spacers.
- In static compression tests with a plate, configuration V1 recorded stiffness increases of 400% with aluminum spacers and 360% with PLA, but the stiffness with PLA decreased by 12.5% when conditioned at 60 °C. Configuration V2 showed improvements of 363.3% (aluminum) and 308.3% (PLA), with a 29.7% reduction for PLA at elevated temperature. Configuration V3 recorded increases of 193% (aluminum) and 192% (PLA), but only an 11% decrease in PLA stiffness at 60 °C. Similar results were observed in compression tests with a cylinder: V1 recorded a 571% increase in stiffness with aluminum, V2 with 425%, and V3 with 219%. For PLA at 60 °C, the decreases were 21% for V1, 33% for V2, and 9% for V3.



(a)



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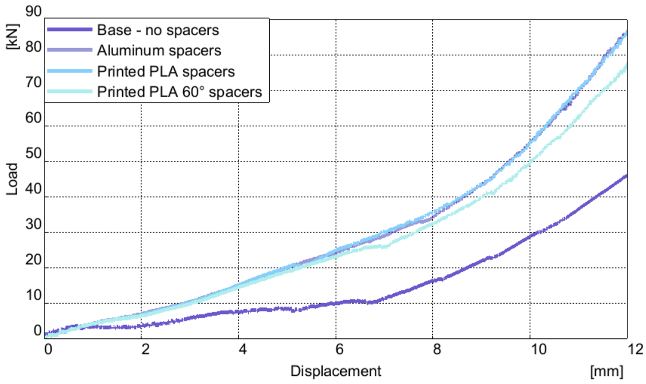
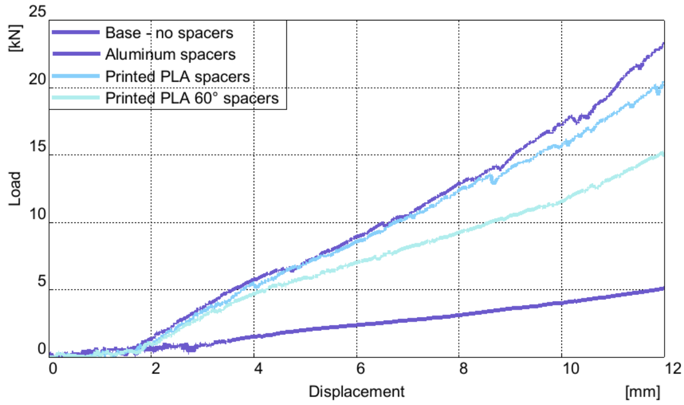
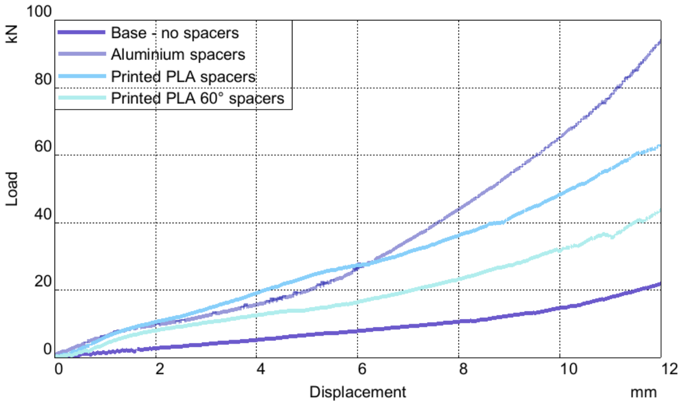


(**c**)

Figure 8. *Force–displacement curve of the compression plate for different cell configurations: (a) V1; (b) V2; (c) V3.*



(**a**)



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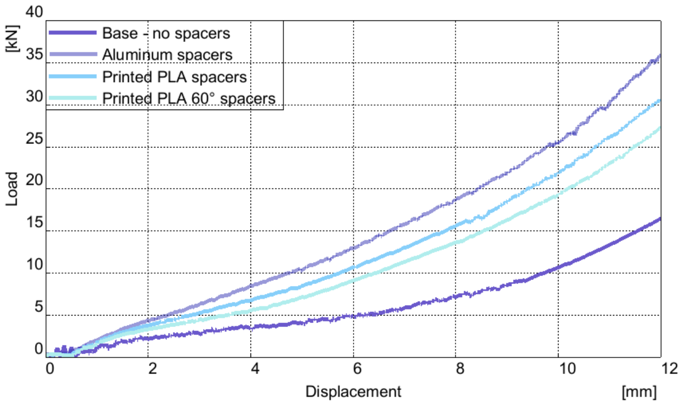
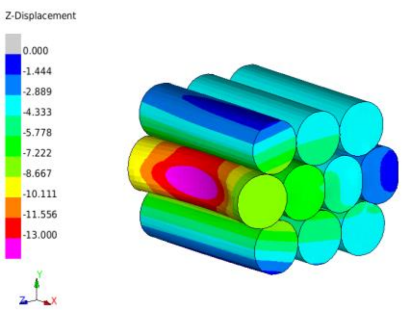


(**c**)

Figure 9. *Force–displacement curve of the compression cylinder for different cell configurations: (a) V1; (b) V2; (c) V3.*

- Dynamic impact tests revealed significant reductions in intrusion into the cell pack. Configuration V1 showed a 42% decrease in intrusion with both aluminum and PLA spacers, with a slight increase at 60 °C. Configurations V2 and V3 also demonstrated improved performance, with intrusion reductions of 22% and 15%, respectively, using PLA.



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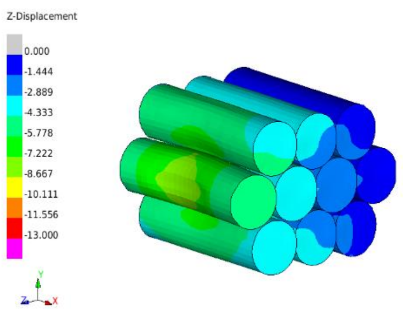

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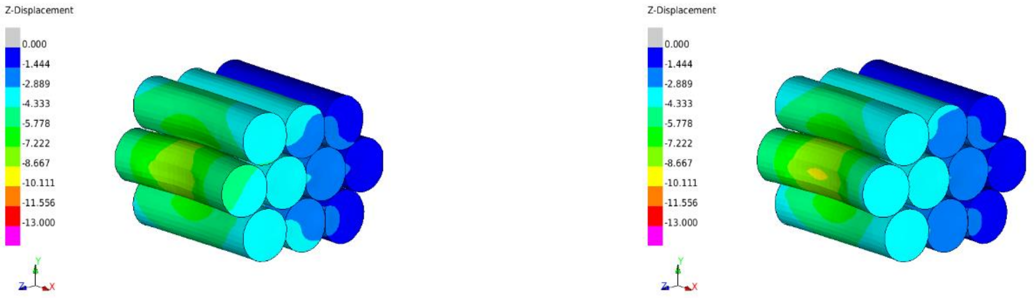
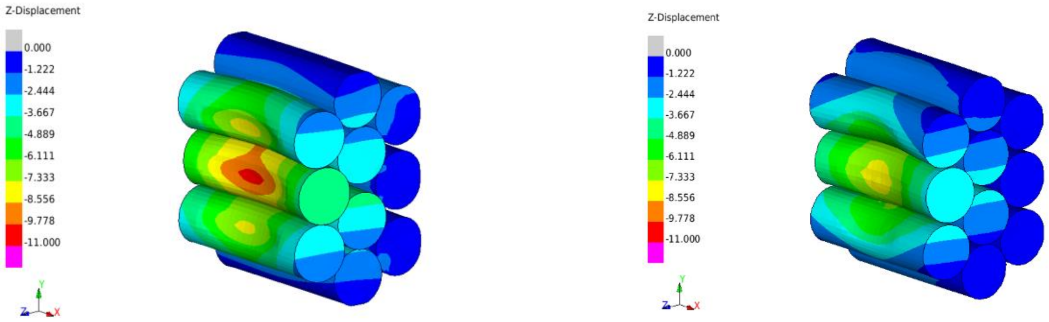
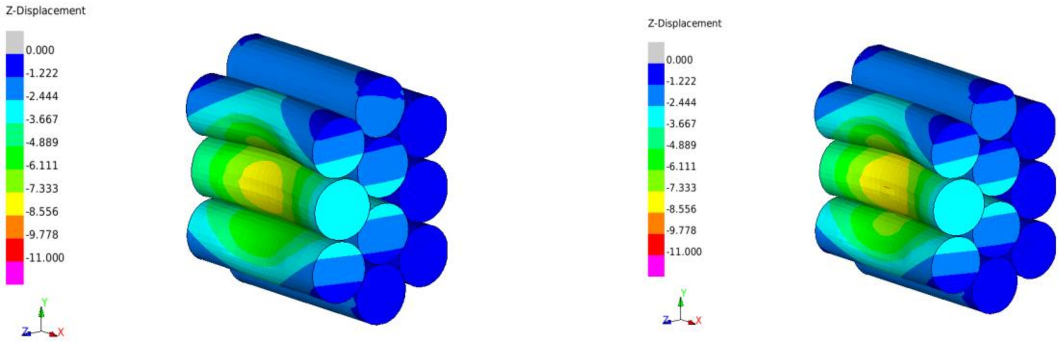


(**c**) (**d**)

Figure 10. *Dynamic loading intrusion in cell configuration V1: (a) without spacers; (b) aluminum; (c) 3D-printed PLA; (d) PLA printed at 60 °C.*

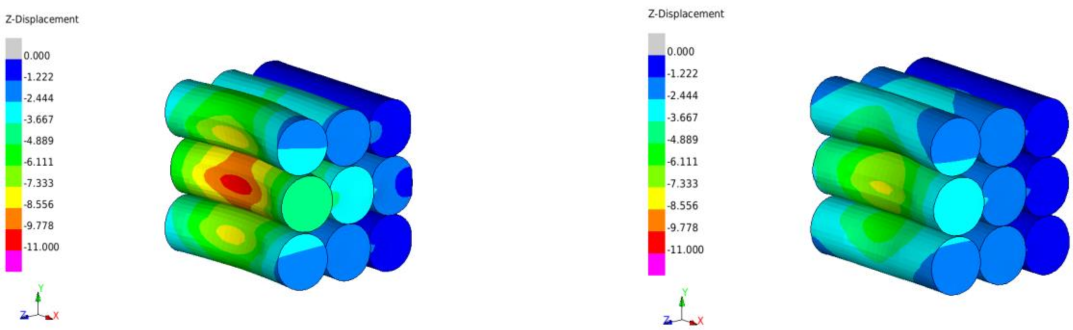


(**a**) (**b**)



(**c**) (**d**)

Figure 11. *Dynamic loading intrusion in cell configuration V2: (a) without spacers; (b) aluminum; (c) 3D-printed PLA; (d) PLA printed at 60 °C.*



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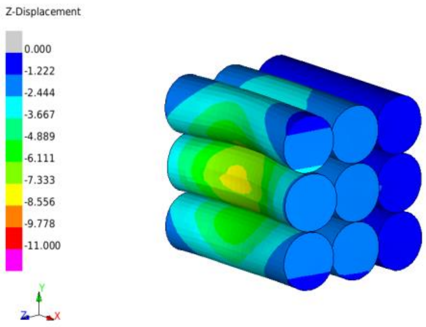

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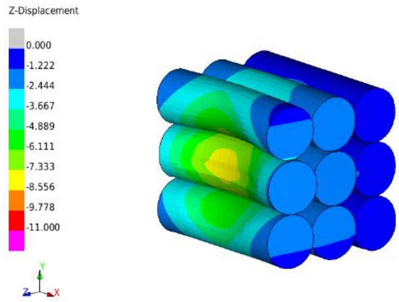

(**d**)

Figure 12. *Dynamic loading intrusion in cell configuration V3: (a) without spacers; (b) aluminum; (c) 3D-printed PLA; (d) PLA printed at 60 °C.*

The final chapter of the personal contribution, ***Impact Analysis of Batteries and Battery Packs within an Electric Vehicle***, addresses the safety issue in an applied and realistic context. At this stage, a dedicated methodology was developed for simulating a lateral impact scenario, as close as possible to real-world conditions and international vehicle safety testing standards. The process began with the conversion and simplification of a conventional vehicle numerical model into one adapted to the architecture of an electric vehicle. A representative volume for the Li-ion battery pack was also modeled, whose structural behavior was validated through numerical simulations. Based on this, a structural optimization study was conducted for an electric vehicle battery, analyzing various design solutions, impact scenarios, and impactor positions, aiming to maximize cell protection. The main contributions of this study are:

- Definition of an original methodology for optimizing an electric vehicle (EV) battery frame, while also optimizing computational resources. The method has potential applications on hybrid platforms—serving both conventional and electric vehicles—or in situations where the battery frame design is carried out without full access to the complete vehicle model data, relying instead on available impact parameters.

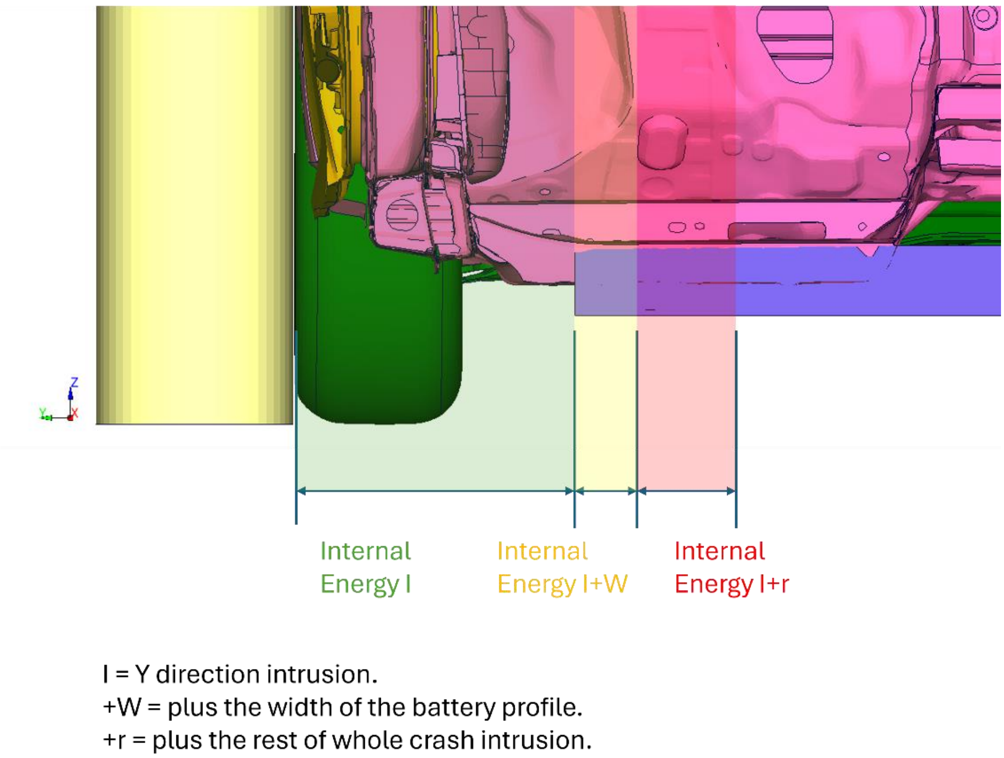

Figure 13. *Energy vs. intrusion diagram.*

- The simulations were carried out using a simplified Toyota Camry model in LS-DYNA, focusing on the side pole impact scenario at two distinct speeds and with the pole positioned in two different locations. The model integrated a fictitious battery frame with virtual mass to accurately reproduce the vehicle's center of mass and provide a realistic visualization of the battery placement. The energy parameters extracted from these simulations were used to define loading cases for optimizing the battery frame, evaluating its performance at impact speeds of 50 km/h and 87 km/h.

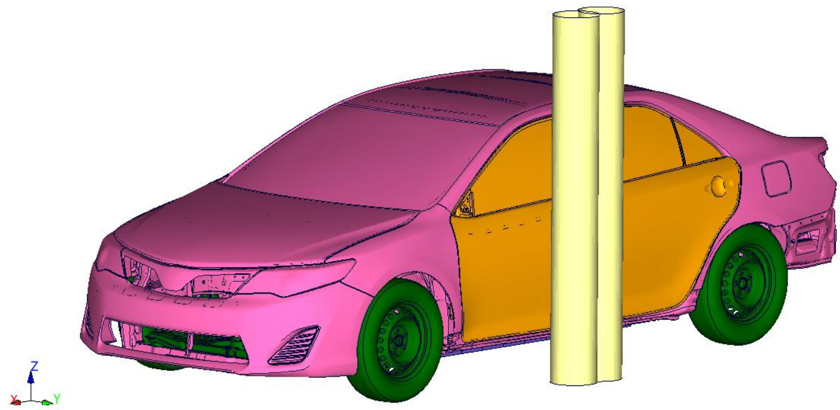

Figure 14. *Pole-type barrier positions.*

- The study also introduces an innovative method for defining the material properties of a representative cell module. This involved simulating the compression of a pack of nine cells, as well as an equivalent solid volume, in order to align the force–displacement curves.

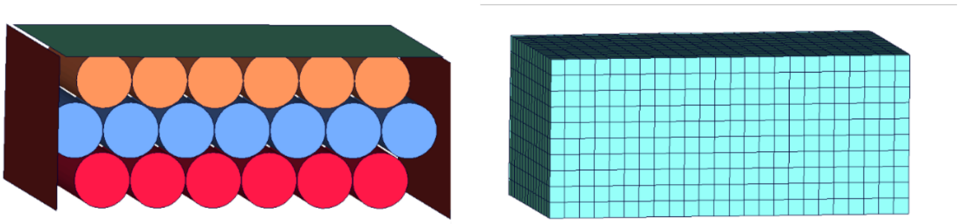

Figure 15. *Simulation of cell compression with doubled dimensions.*

- For the frame optimization process, four loading cases were defined, involving pole impact at two speeds, 50 km/h and 87 km/h, and in two positions: one nominal and another shifted by +200 mm along the X-axis. These scenarios were used to evaluate the behavior of different structural configurations.

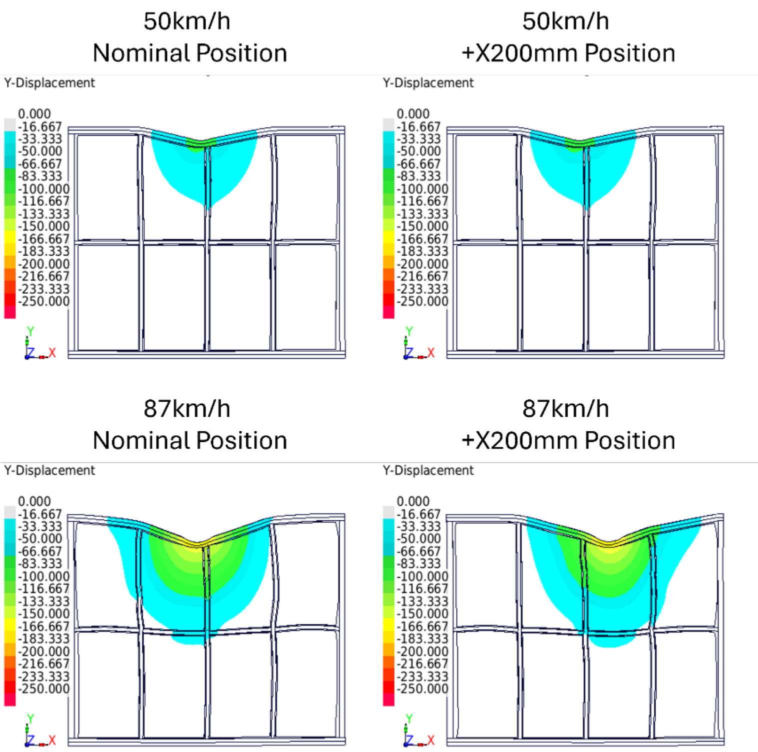

Figure 16. *Intrusion values for configuration V1.*

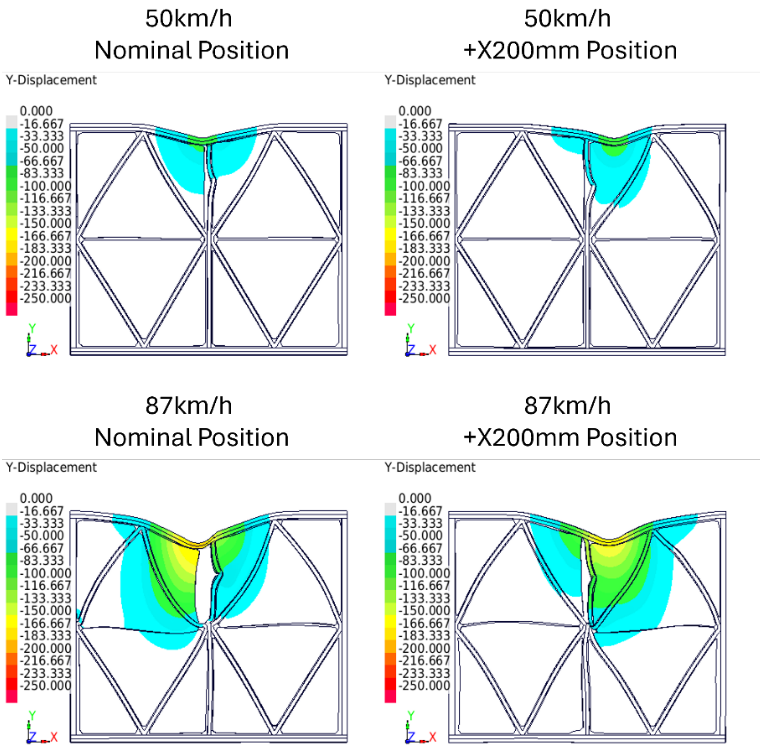

Figure 17. *Intrusion values for configuration V2.*

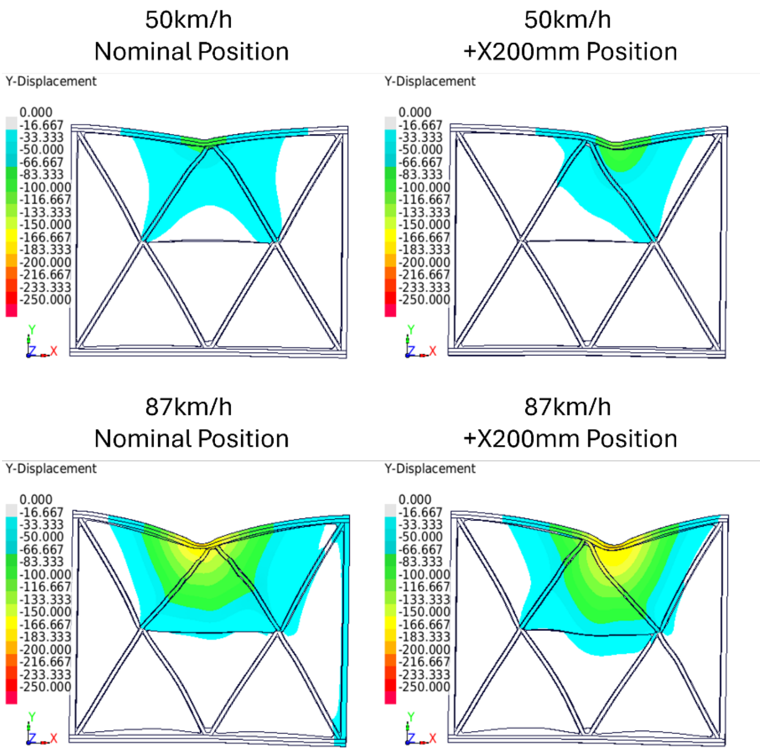

Figure 18. *Intrusion values for configuration V3.*

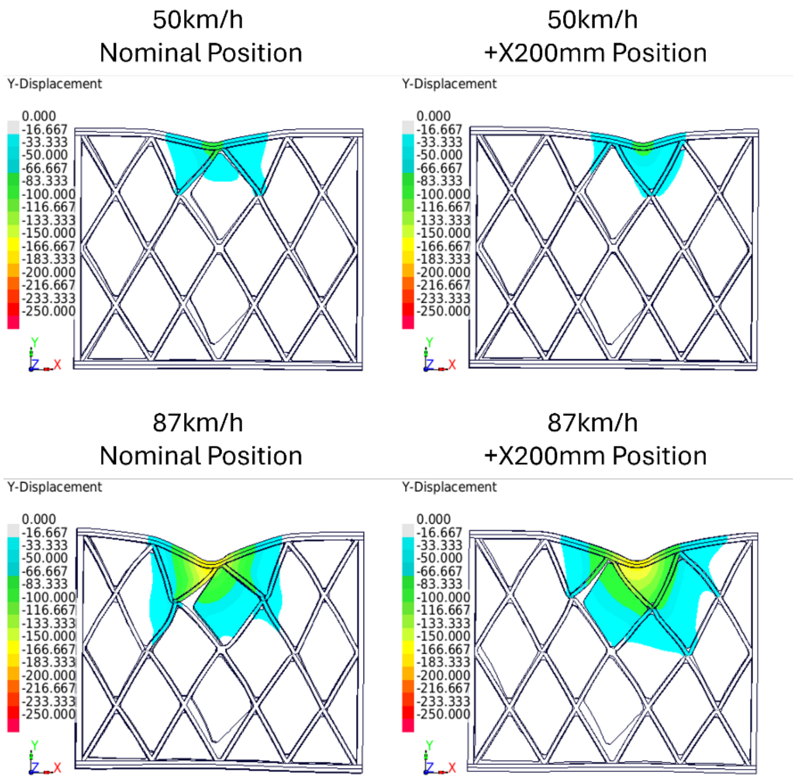

Figure 19. *Intrusion values for configuration V4.*

- The proposed methodology offers significant computational advantages by allowing the extraction of essential impact parameters from a full vehicle model and applying them in a dynamic loading scenario focused exclusively on the battery. Compared to traditional approaches, this method eliminates the need for a complete vehicle model, requiring only the key impact parameters. As a result, computational effort is greatly reduced, and iterative optimizations can be performed directly on the battery model, enabling rapid evaluation of different configurations.

General conclusions:

In conclusion, the topic addressed in this paper was treated in a broad and integrative manner, covering all essential stages for evaluating the integrity of Li-ion batteries in the context of electric vehicles. From an extended analysis of the specialized literature to the development of advanced numerical models calibrated with experimental data, the research focused on achieving a balance between modeling accuracy and computational efficiency, by developing qualitative numerical material models.

The contributions align with a major area of interest in current literature—battery safety under impact or mechanical abuse—and include: the development of FEM models for individual cells, with variations from detailed descriptions to optimized homogenized forms; the proposal of a robust structural reinforcement solution for packs through the use of spacers, without affecting energy capacity; validation of numerical models through experiments, confirming the usefulness and accuracy of the models used; a study to improve battery safety in electric vehicles; and the development of a methodology for applying a realistic dynamic load in lateral impact simulations.

All these results are supported by works published in high-impact scientific journals (Q1 and Q2), confirming the scientific and practical relevance of the research conducted.

Published WoS-Indexed Papers:

1. Muresanu, Adrian Daniel, Dudescu, Mircea Cristian. "Numerical and experimental evaluation of a battery cell under impact load." *Batteries* 8, no. 5 (2022): 48. https://doi.org/10.3390/batteries8050048, WOS: 000803336900001 IF 4,6, Q2
2. Muresanu, Adrian Daniel, Dudescu, Mircea Cristian. "Modelling of a Cylindrical Battery Mechanical Behavior under Compression Load." *Batteries* 10, no. 10 (2024). https://doi.org/10.3390/batteries10100353, WOS: 001342849600001, IF 4,6, Q2
3. Muresanu, Adrian Daniel, Dudescu, Mircea Cristian. "FEM Study on Enhancing Crashworthiness of Cylindrical Li-Ion Battery Packs Using Spacers Between the Cells." *Applied Sciences* 15, no. 5 (2025): 2720, https://doi.org/10.3390/app15052720, WOS: 001442414800001, IF 2.5 Q1.
4. Muresanu Adrian Daniel, Dudescu Mircea Cristian, David Tica. "Study on the Crashworthiness of a Battery Frame Design for an Electric Vehicle Using FEM." *World Electric Vehicle Journal* 15, no. 11 (2024): 534. https://doi.org/10.3390/wevj15110534, WOS: 00136655750000, IF 2.6 Q2

Conference Papers:

1. Adrian D. Muresanu, Vasilica Cimpoies, Mircea C. Dudescu, "Numerical Investigation of Horseshoe Lattice Structures for Crashworthiness Improvement of a Battery Frame", The 3rd International Conference on Mechanical System Dynamics (ICMSD2025), September 23-27, 2025, Cluj-Napoca, Romania (accepted for presentation)

Citations of Published Papers

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Publication	Google Scholar citations	Web of Science citations
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2	1	1
3	1	-
4	1	1