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BATTERY CRASH SIMULATION IN ANSYS LS-DYNA

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Abstract: *Nowadays, lithium-ion batteries are considered as the most efficient source of power for electric vehicles (EVs). With the increasing utilization of EVs, the requirements for higher performance, lower weight and improved safety are also growing. These demands can be fulfilled by an improved battery design, which consists of decreased battery frame mass or higher number of battery cells. However, with these improvements come several negative aspects, such as higher risk of battery frame intrusion or lower heat dissipation due to reduction of space between the cells. Due to these factors, the risk of battery damage is rising, thus it is crucial to predict and better understand the behavior of the battery cells during critical situations, such as vehicle crash. Ansys LS-DYNA is a useful tool for the evaluation of battery cells during abusive scenarios. It offers the creation of multi-physics model that is able to predict coupled mechanical, electrical and thermal responses. This model is sufficient for the assessment of battery cell response to short-circuit, which can lead to uncontrollable, self-heating state called thermal runaway. This state poses the greatest safety risk for Li-Ion batteries. This paper focuses on risk assessment of traction battery during crash and overcharging simulations.*

Keywords: Battery, LS-DYNA, explicit, multi-physics, crash.

1. Introduction

Ansys LS-DYNA provides the capability to simulate battery cells under typical operating conditions, as well as in scenarios involving potential overloading and short-circuit events. LS-DYNA uses one-code strategy, integrating solvers cohesively. Particularly in battery simulations, the main utilized solver is the resistive heat solver. From the electromagnetic (EM) solver, the Joule energy term $\dot{q}_{joule}$ can be extracted (Ansys Inc., 2020):

$$\dot{q}_{joule} = \int_t^{t+1} \frac{j^2}{\sigma} dt, \tag{1}$$

which acts as a volumetric heat source term in the thermal equation:

$$\frac{\partial T}{\partial t} - \alpha \Delta^2 T = \dot{q}_{joule}, \tag{2}$$

where j is current density, is σ electrical conductivity and α is thermal diffusivity.

The electrochemical reactions within the battery cell are represented by a phenomenological model known as the Randles circuit. Despite its simplicity, this model suitably captures the behavior of the battery across various operational scenarios.

LS-DYNA offers several approaches to battery modeling. There are two micro-scale methods which are based on discretizing individual battery cell layers using solid or thick-shell elements. These models allow detailed analyses of single battery cells. However, due to the typically thin battery layers, the finite element mesh has small element dimensions along the cell thickness, thereby increasing computational time. Consequently, these methods prove inadequate for modeling battery modules or entire packs with numerous cells. In such cases, a global approach is favored, wherein the battery cell is considered as a homogeneous orthotropic continuum. This modeling strategy enhances computational efficiency.

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The risk of short-circuiting poses a significant threat to batteries, potentially resulting in catastrophic damage to the cell. This occurrence may arise from various factors. For example, overcharging the battery elevates its temperature, leading to possible damage to the separator layer, thereby initiating a short circuit and triggering a hazardous exothermic reaction known as thermal runaway. During thermal runaway, the temperature of the cell increases rapidly, presenting a considerable risk of fire or explosion. External heat sources can affect the battery cell in same negative manner. Furthermore, short-circuiting can be induced by physical deformation of the battery cell, such as nail penetration, causing mechanical harm to the cell separator and establishing an undesirable internal electrical connection between the electrodes.

This paper contributes to the SAFEBATT project, which is focusing on the advancement of a robust early warning system for battery failure and the design of a self-extinguishing and cooling system for battery packs to enhance its safety. In 2023, SVS FEM was tasked with conducting numerical simulations of the traction battery crash test in accordance with the ECE 100 standard, along with electro-thermal simulations. The results from these numerical simulations are presented within this paper.

2. Battery cell testing

The analyzed traction battery comprises 8 battery modules, each housing 24 cells. To calibrate and optimize the numerical model of a single battery cell, a series of mechanical, thermal, and electrical tests were conducted. Regarding the mechanical aspect of the battery, the cell consists of an inner series of diverse chemical compound layers, commonly referred to as the "jellyroll", encased in an outer aluminum alloy casing. Four quasi-static mechanical tests were conducted to capture a broad spectrum of loading scenarios (see Fig. 1). Additionally, alongside force-displacement measurements, voltage and temperature were recorded to detect potential short-circuiting of the cell resulting from possible penetration of the separator layer.

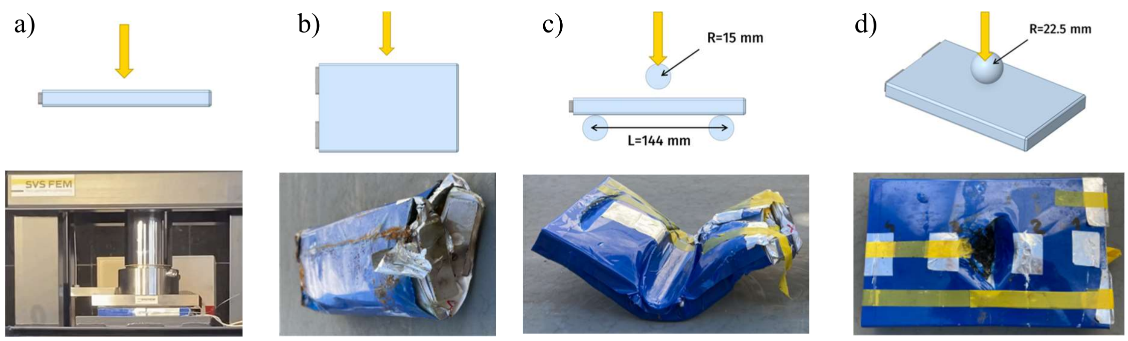


Fig. 1: Deformed specimens - a) flat compression, b) lateral compression, c) 3-point bending, d) punch.

The deformed cell shapes are depicted in Fig. 1. Short-circuiting was observed during the lateral compression test, coinciding with buckling deformation, culminating in battery ignition at the end of the loading sequence. Although thermal runaway was expected during the punch test, there was no notable sharp decline in the voltage that would consequently lead to an increase in temperature. A possible explanation for this phenomenon is the larger diameter of the spherical indenter, which only compresses the jellyroll layers without perforating them. Obtained force-displacement curves were utilized to calibrate the material model of the cell's FE model.

Correctly defining the electrical and thermal properties within the numerical model of the cell is necessary for assessing voltage trend and heat conduction within the battery. Three electrical tests were conducted to acquire the parameters of the Randles circuit. One thermal test was executed. In this thermal test, the base of the cell was subjected to external heating until a short-circuit occurred, resulting in a cell explosion (see Fig. 2). The explosion happened because the cell was fastened by a thick rope encircling the upper section of the battery, preventing cell movement. However, due to this constrain on the upper surface, the accumulated internal pressure could not be adequately released through the top safety vent. It is assumed that in the event of pressure release, the battery will likely ignite.

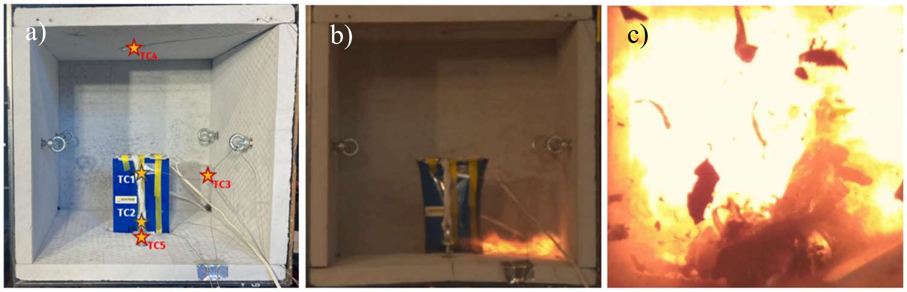


Fig. 2: Battery cell in the chamber a) with thermocouples, b) immediately before the explosion, c) during the explosion.

3. Crash simulation of traction battery

Based on the geometry, the finite element (FE) model of the entire traction battery was developed (see Fig. 4a). In most traction battery components, a bilinear material model was employed. Specifically, the bilinear material model was assigned to the battery cell's aluminum casing. Additionally, an orthotropic material model was applied to represent the homogeneous solid jellyroll of the cell. Parameters associated with these material models were iteratively adjusted to align with experimental results.

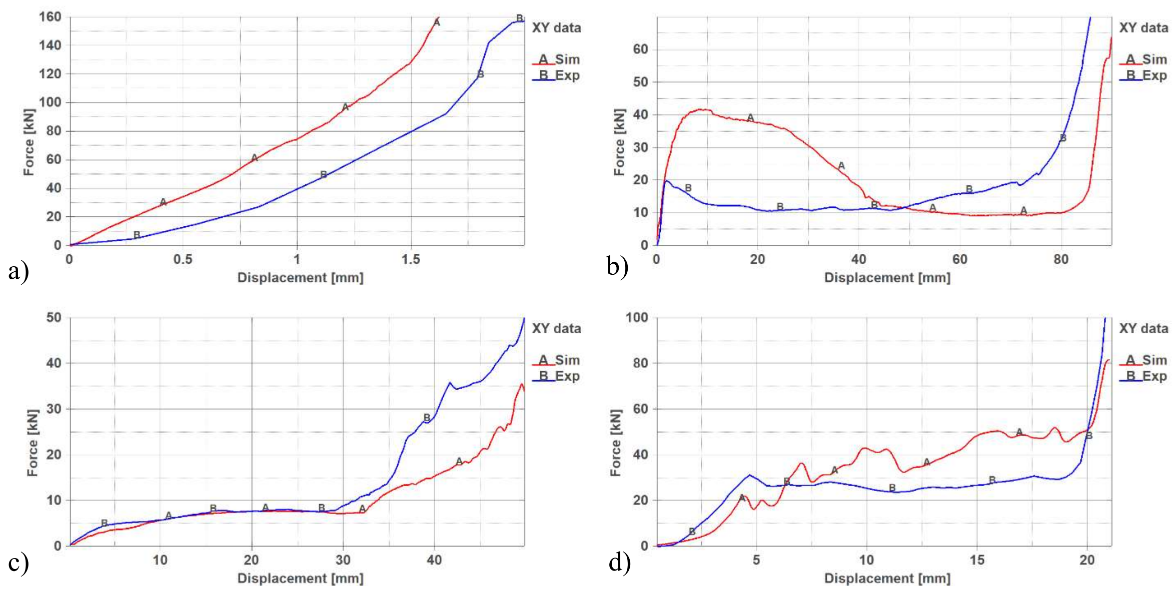


Fig. 3: Comparison of force-displacement curve between simulation and experiment a) flat compression, b) lateral compression, c) 3-point bending, d) punch.

Comparing the results obtained from simulations with experimental data, a perfect alignment between the force-displacement curves was not achieved (see Fig. 3). It is important to note that the jellyroll comprises numerous layers, each possessing different mechanical properties. Consequently, at the microscale level, local deformation processes (failure, buckling, delamination, etc.) within these layers cannot be accurately captured by a homogeneous model with a coarse mesh.

To date, only the structural part of the model has been solved in the crash simulation utilizing an explicit solver. However, the following phases of the project aim to incorporate electromagnetic (EM) and temperature solvers into the analysis.

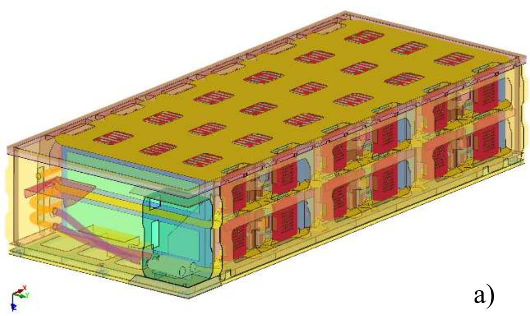
An acceleration-time curve conforming to ECE 100 standard specifications was applied to the traction battery. Stress and strain distributions were evaluated across the battery frame, bolts, and individual cells. According to the findings of the numerical simulation, no compromising of structural integrity was observed within the traction battery. Moreover, cell deformation was negligible, thereby reducing the probability of an internal short-circuit event.

4. Electro-thermal simulation of battery module

In the current stage of the project, the battery cell is considered as rigid in terms of mechanical properties, since stress and deformation analyses of the cell/module are neglected in the electro-thermal simulations presented in this paper.

For the electromagnetic (EM) part of the model, a homogenized approach to the battery cell modeling is employed. Parameters such as the temperature at which short-circuiting occurs and the internal battery resistance were obtained from experimental data. Typically, a short-circuit event triggers an exothermic reaction accompanied by heat dissipation. However, this reaction was not observed in the overheating test due to aforementioned imperfections in battery mounting. Nevertheless, the exothermic reaction is still accounted for in the simulation, but the exothermic rise of the temperature, and post-short-circuit behavior are estimated.

Following the development of the FE model of the battery module, simulations were conducted to investigate the effects of overcharging cell number 1 (see Fig. 4b). Heat propagation within the battery module was monitored, revealing that the adjacent cell, number 2, also experienced heating due to the thermal runaway initiated by the first battery cell. Consequently, a short-circuit occurred in the cell number 2 area where the critical temperature was reached. Cell number 3, however, did not reach the critical temperature threshold, thus avoiding a short-circuit event.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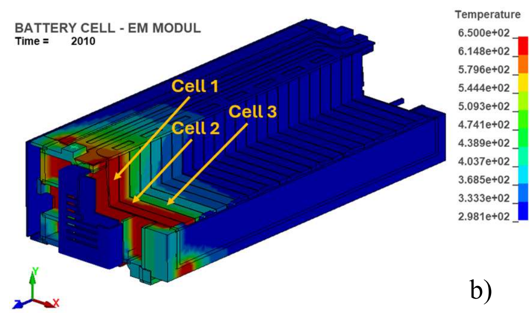

b)

Fig. 4: a) Traction battery FE model for crash simulation, b) temperature of battery module during overcharging simulation – cut section view.

5. Conclusion

Ansys LS-DYNA was employed to create the FE model and conduct simulations of the battery under diverse loading conditions. A homogeneous battery cell modeling approach was adopted. To capture the multi-physics properties of the cell model, four quasi-static mechanical tests, one overheating test, and three electrical tests were conducted.

The FE model of the traction battery was developed to simulate mechanical crash test in accordance with ECE 100 standard. Stress and strain distributions across the entire battery and its individual cells were analyzed. According to the outcomes of the numerical simulation, no compromise of the structural integrity of the traction battery was observed. Moreover, there were no instances of cell penetration, reducing the probability of an internal short-circuit event.

In the electro-thermal simulation, a scenario involving the short-circuiting of one cell within the battery module was simulated, with subsequent observation of heat transfer within the module. In order to enhance electro-thermal simulation, additional experimental investigations are warranted to accurately characterize the thermal and electromagnetic aspects of the battery model, such as external shorting, heat propagation among multiple battery cells, or nail penetration. Furthermore, future considerations should include the effect of strain rate on resulting cell stresses.

References

Ansys Inc. (2020) *AnsysLearningHub.* Online. Ansys, Inc.