Full Electric Vehicle Crash Simulation Using Coupled Thermal-Electrical-Mechanical Analysis

Chenxi Ling, Leyu Wang, Cing-Dao (Steve) Kan and Chi Yang

Center for Collision Safety and Analysis,
George Mason University, Fairfax, Virginia, USA

Abstract

The safety of electric vehicles (EVs) has become increasingly important as the number of EVs has grown rapidly in recent years. This work presents a system solution to model the full EV structural crash analysis together with its active battery cells using a thermal-mechanical-electrical coupled analysis. This multi-physics analysis predicts the sequence of events that could lead to thermal runaway and battery fire. In previous work, a representative battery cell model was first developed based on matching the cell dimensions and the total amount of material in a realistic cell. Each battery component was modeled separately with realistic mechanical, electrical, and thermal material models. To improve computational efficiency, the electric circuit of the battery was modeled with the resistant heating solver in a user defined *Randles-Circuit* Model. The external short circuit test and punch test were used to calibrate the circuit dynamic response and mechanical behavior of the battery. It was demonstrated that the model was able to predict current density, Ohm heating power, and temperature distribution contours on each battery component layer. The model could capture the local heat generation caused by the coupling effect in the punch test of a discharging cell. In this study, the battery cell model is further extended, and a new battery modeling methodology is implemented to build a generic electric vehicle model with multiple live cells in circuit connection. In addition to predicting deformation and acceleration in the same way as the mechanical-only crash simulation, the current multi-physics EV model also provides the current density, voltage, heat generation, and temperature distribution caused by both mechanical loading and electric short circuit. A simulation case of a full EV model with 24 active battery modules under the side impact with a moving deformable barrier (MDB) is selected to demonstrate the feasibility of running multi-physics simulation for EV crash analysis. It takes about 24 hours to run the side impact simulation for this full EV model on a 32-core cluster for a crash event of 0.2 seconds. Simulation results have shown that the present multi-physics model based on thermal-mechanical-electrical coupled analysis is able to predict the thermal runaway and battery fire in a full EV crash simulation.

1 Introduction

In recent years, an increasing number of EV accidents have happened on the road causing the loss of property and life. It's necessary to understand the crashworthiness of EV by developing a predictive finite element model. Recent works on battery material modeling have been done by some researchers[1]. Besides regular structural deformation, EV is also associated with a potential fire hazard in thermal-runaway mechanism, as it is shown in Figure 1. Predicting thermal runaway is a key point of battery multi-physics modeling. Thermal runaway describes a process, in which increasing temperature causes the release of more energy that further increases the temperature. This work focuses on the ability to capture the phenomenon involving the coupling of multiple physics that leads to the starting point of battery thermal runaway. Therefore, we can predict whether the EV will catch fire or not under a specified crash scenario. The event after the thermal runway, i.e., the ignition and combustion process, is beyond the scope of this study.

The lithium-ion battery modeling methodology consists of two parts, mechanical modeling and multi-physics analysis. The battery cell is modeled with a representative geometry: Each cell component, including cathode current collector, cathode, separator, anode, anode current collector, is modeled separately with a representation geometry. A user-defined voltage source[2] is utilized to model the capacitor so the Randles circuit[3] can be modeled with resistant heating solver. The multi-physics model combines the thermal solver, electric resistant heating solver, and mechanical solver together in a fully coupled LS-DYNA simulation. The verification test for LS-DYNA electric solver is included in the appendix A. It can be observed that the electric circuit simulation with LS-DYNA reaches the same accuracy level as classical circuit simulation.

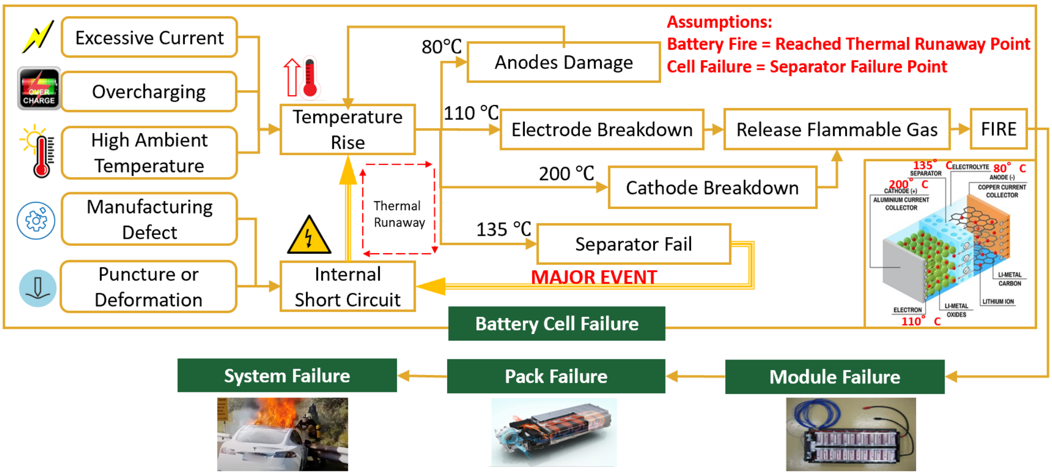

Figure 1 EV Fire Caused by Thermal-Runaway of the Lithium Ion Battery

2 Methodology and Results

2.1 Methodology Development of Representative Single Cell Model

The method for modeling battery cell in previous study[2] is summarized here: The single cell model is based on the structure and dimensions of a realistic porch cell lithium-ion battery. The exterior dimensions are $50mm \times 30mm \times 5.07mm$. As shown in Figure 2, five different parts are used to represent the five different battery components (cathode current collector, cathode, separator, anode, anode current collectors). A first-order Randle circuit is used for modeling the battery's electrical behavior. A user-defined voltage source is utilized to model the capacitor so the *Randles-Circuit* can be modeled with resistant heating solver. This model is demonstrated to be able to predict the thermal, electrical, and mechanical behavior under: 1) normal discharging, 2) external short circuit test, 3) hemispherical punch test[2].

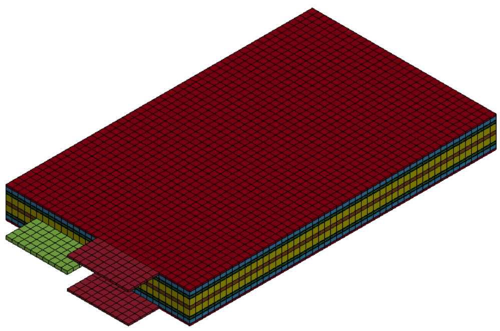

Figure 2 Representative Single Cell Model

2.2 EV Model

Adopting the modeling methodology in the previous section, the multi-physics EV model is developed from the single cell model to a 4-cell module model and finally to a full EV model. The battery cell and battery module are modeled based on a disassembled and laser scanned first-generation Nissan Leaf battery. The dimensions of battery cell are $261mm \times 216mm \times 7.9mm$ and the dimension of battery module is $303mm \times 223mm \times 35mm$. The full EV model is a generic model based on the Google Waymo first-generation autonomous vehicle. The body-in-white structural part is referenced from the updated version of Toyota Yaris crash analysis model. An EV model with 24 active battery modules ($8.6K$ elements for each module) is developed with a total of $698K$ elements. This EV model is shown

in Figure 3. The initial time step for thermal solver is $1e-3$ second and the constant time step for electrical solver is $1e-5$ second. *EM_ISOPOTENTIAL and *EM_ISOPOTENTIAL_CONNECT are used for electric circuits[4]. Four battery cells in a module features realistic circuit connection as in the Leaf Module, and the battery modules in battery pack are connected in series.
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_THERMAL is used for thermal and mechanical contacts.

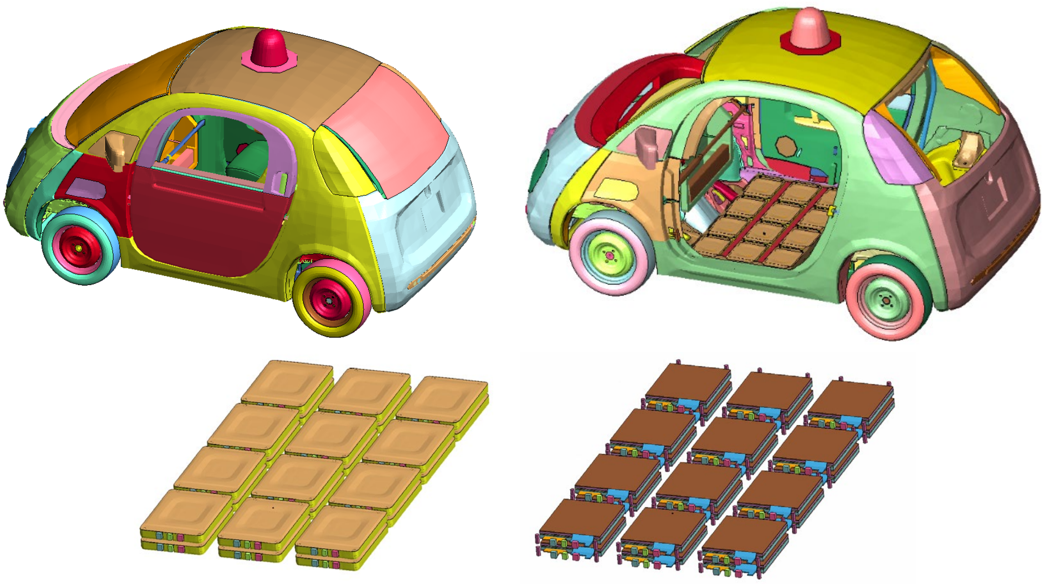

Figure 3 EV Model (Top Left), Battery Pack in EV Model (Top Right), 24 Battery Modules (Bottom Left), Internal Structure of Battery Module (Bottom Right).

2.3 Modeling of EV with Normal Discharging or External Short Circuit

An external resistant of 1Ω is connected to represent the discharging of battery under normal operation. Figure 4 shows the current density and temperature distribution in a normal discharging condition.

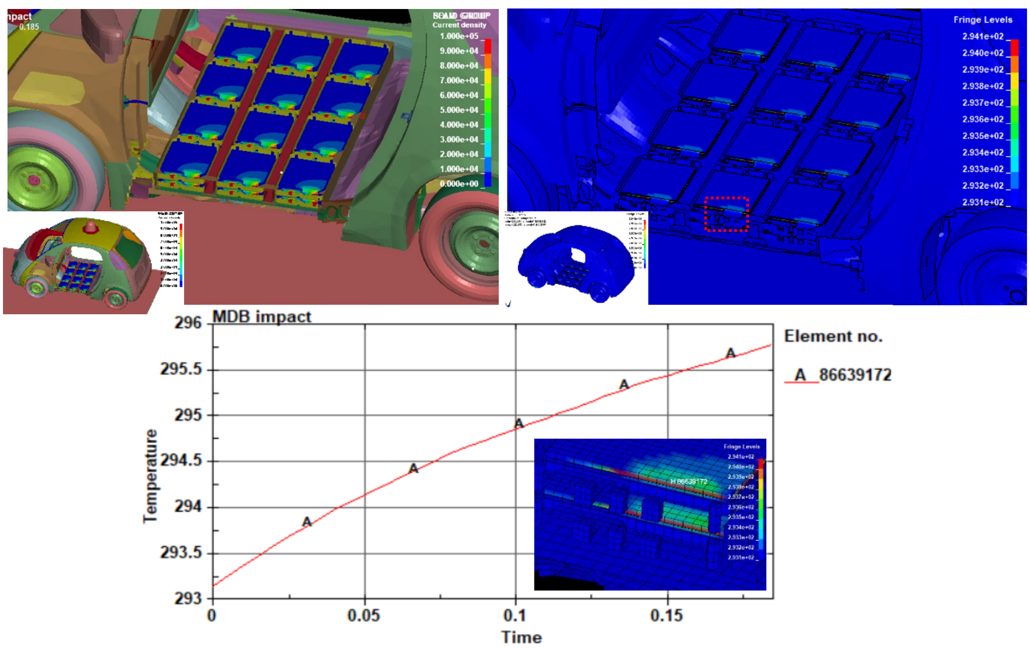

Figure 4 Normal Discharging: Current Density (Top Left); Temperature in Kelvin (Top Right); Highest Temperature inside the Battery (Bottom)

It can be observed from Figure 4 that the area with higher current and heat generation is closer to the current collector tab, where all electrons must pass through. Simulation results also show that the temperature generated by electric heating mainly comes from the cathode layer. This is because the cathode material has much higher resistivity than other materials in the battery cell. The heat generated at cathode layer is gradually transferred to other cell parts of the battery and eventually to the EV structure.

An external short circuit model is used to demonstrate the transient thermal-electrical analysis. The increase of the temperature is much faster in the external short circuit case (about 3000°C in 0.2 seconds, assume no material failure) than that of the normal discharging condition case (2°C in 0.2 seconds). Realistically, the cell temperature will rise to 200°C in 0.005 seconds in the external short circuit case. At that temperature, the separator will melt, and the thermal runaway and fire become inevitable.

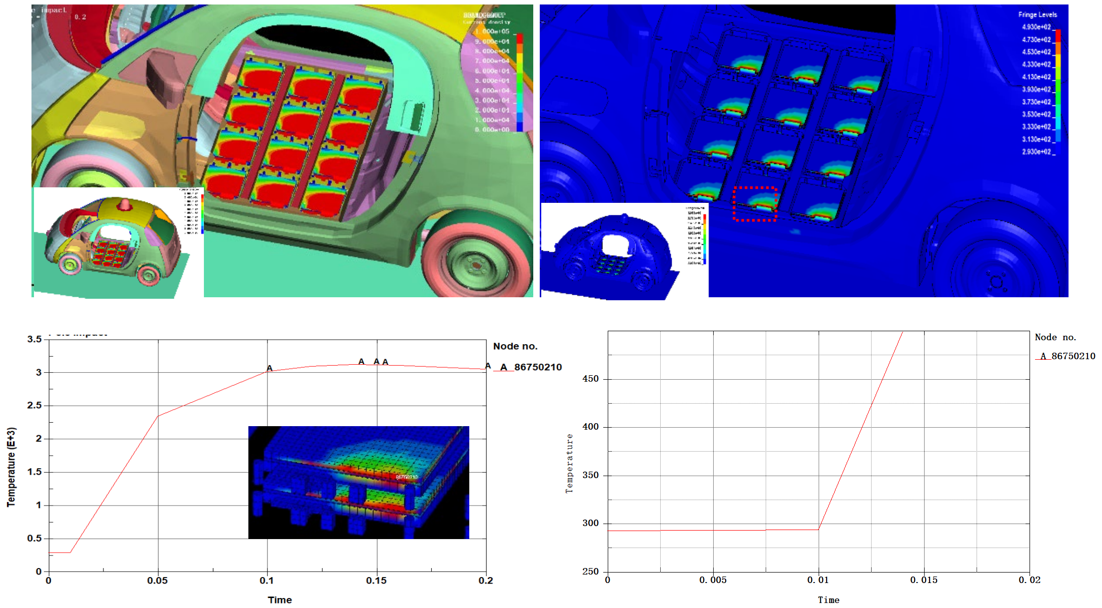

Figure 5 External Short Circuit: Current Density (Top Left); Temperature in Kelvin (Top Right); Highest Temperature inside Battery (Bottom Left); Temperature Rose to 200 K in 0.005s in External Short Circuit.

3 A Full Vehicle Crash Simulation - MDB Side Impact of EV with Active Cells

To demonstrate that coupled active cells model can be used in full vehicle simulation, an EV MDB side impact simulation is conducted based on FMVSS214 configuration. The impact speed of the MDB in this case is 62 km/h. The battery system is connected in a normal discharging situation. The simulation of MDB side impact takes 18 hours and 40 minutes to simulate the crash event of 0.2 seconds. Figure 6 shows an EV MDB side impact model and the simulation results. Figure 7 shows the corresponding temperature contours, and Figure 8 shows the temperature time history for the highest temperature location in the area circled in Figure 7.

Figure 6 MDB Side Impact Model Left) and Simulation Result (Right)

From the simulation results, it can be observed that the temperature increase is caused by both mechanical impact and electric heating. It is also noted that the temperature keeps on increasing due to electric heating even after the impact event is ended. The results clearly show that the temperature increases faster in the area closer to the impact area due to the increase of electric heating power at the deformed area of the battery cell. In addition, the rate of the temperature increase slows down due to thermal transfer and thermal radiation. Furthermore, it can be observed that the highest temperature increase in the battery is 2.5°C at the time of 0.2 seconds. In this study, the battery compartment is not significantly deformed. As a result, a thermal runaway event does not occur in this EV MDB side impact simulation.

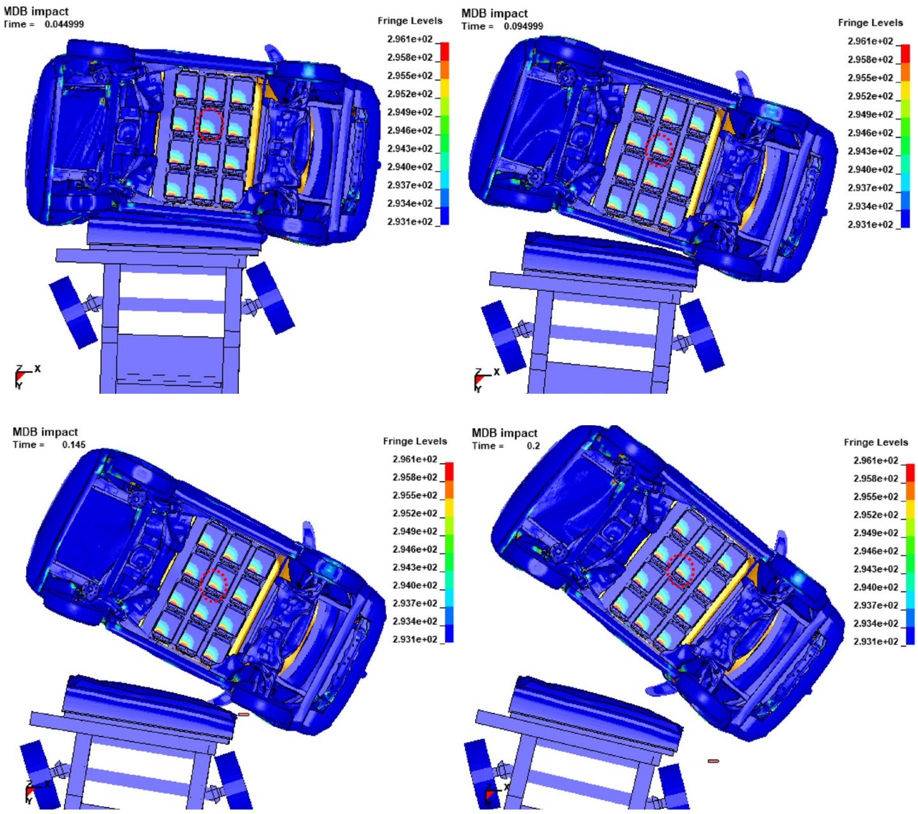

Figure 7 Temperature Contour in Kelvin at t = 0.045s (Top Left), 0.095s (Top Right), 0.145s (Bottom Left), 0.2s (Bottom Right).

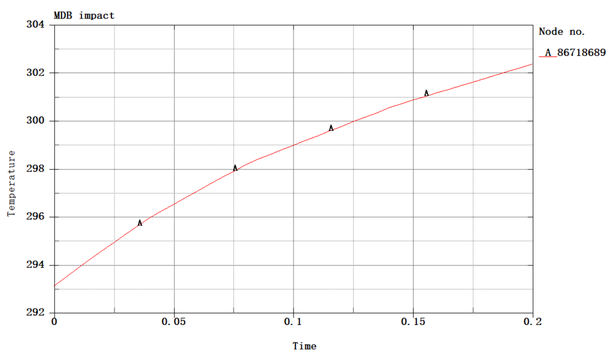

Figure 8 Temperature Time History at Highest Temperature Location.

4 Summary

This paper implemented a new methodology to perform EV crashworthiness simulation using thermal, electrical, and mechanical coupling. This method enables the thermal runaway simulation to predict the battery behavior under mechanical impact, electrical fault, or thermal abuse. Specifically, different components in the battery cell are modelled separately with realistic material properties, which describe the mechanical, thermal, and electrical behavior more accurately than that of homogenized models. This coupled battery model can predict the failure point of individual battery part. It can be used in an EV impact simulation with live electric circuit to predict thermal runaway. This modeling technique provides a more practical approach to model the coupling effect of EV crashworthiness using current computational resources.

The EV model used in the study is a genetic model: the material models are based on literature, not from any reverse engineering; the structure does not represent the actual vehicle. In the future, an EV model should be developed using reverse engineering process to better understand the EV impact behavior. The automobile, aerospace and other related engineering field can use this methodology to better understand battery safety and perform simulation-based design analysis. This methodology can help develop more efficient and cost-effective EVs in the future. The current battery modeling framework is not limited to the lithium-ion battery cell. It can be used for other type of battery cells as well.

5 Acknowledgement

Special thanks to Kevin Arellano-Moya, Rudolf Reichert, Chung-Kyu Park, and Dan Brown of Center for Collision Safety and Analysis at George Mason University for their help and support of this work.

Reference

1. Zhu, J., Wierzbicki, T. & Li, W. A review of safety-focused mechanical modeling of commercial lithium-ion batteries. *Journal of Power Sources* **378**, 153–168 (2018).
2. Wang, L., Ling, C., Kan, C.-D. & Yang, C. A coupled thermal–electrical–mechanical analysis for lithium-ion battery. *J. Micromech. Mol. Phys.* 1–10 (2022) doi:10.1142/S2424913021420108.
3. Randles, J. E. B. Kinetics of rapid electrode reactions. *Discuss. Faraday Soc.* **1**, 11 (1947).
4. Livermore Software Technology. LS-DYNA Manual Volume III Mutliphysics.

Appendix

The Whiston Bridge Simulation is presented as a validation case for Electric Resistant Solver in LS-DYNA.

Finite element method in electric simulation – A Wheatstone bridge shown in Figure A1 is a typical electric circuit used to measure unknown electrical resistance. It is selected as a benchmark problem to verify the accuracy of electric solution with finite element methods. An analytical solution is acquired from professional electric engineering software and compared with the result from a finite element analysis result with LS-DYNA. The FEM simulation is modeled with shell elements and proper connections. The resistant *R* is defined by setting the material conductivity and the shell geometry to a certain value. Thus, the solution from finite element method represents the solution of this electric circuit.

Here we have

$$R = l/\sigma A \tag{1}$$

where σ is conductivity, l is conductor length and A is cross-sectional area of the current flow.

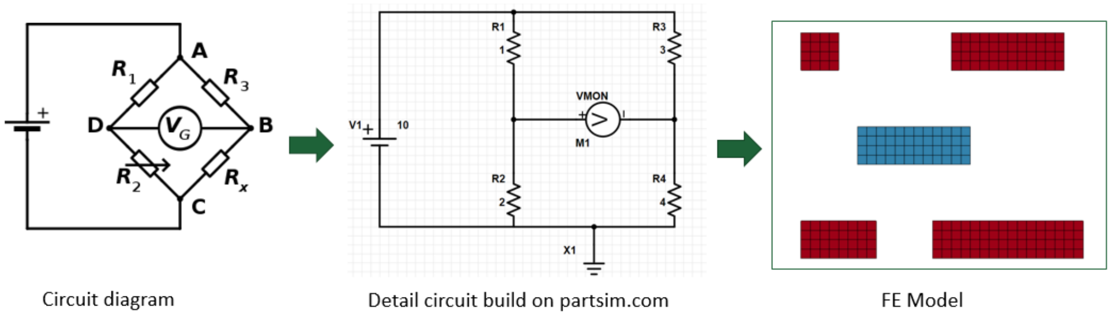

Figure A1: Wheatstone Bridge: Circuit (Left). Diagram in Professional Electrical Simulation Software (Middle). Model in LS-DYNA (Right)

The theoretical result from the electric engineering software show $V_{GTheo} = 0.95238\,V$. The result from FEM simulation is $V_{GFE} = 0.95163\,V$. The error between theoretical result and simulation result is *0.0787 %,* the result verifies that a finite element method is capable to perform finite element analysis on an electric circuit.