Crash Safety of Lithium-Ion Batteries for Electric Vehicles

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Vehicle Crashes and Testing

Santa Barbara Arts TV
YouTube Partner
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Breaking Global News!
Battery Packs in T Configuration

Chevy Volt

Fisker Karma
Battery Packs under the Floor

BMW i3 Concept  
Tesla model S  
Mitsubishi i-MiEV
EV, PHEV Battery Packs

A123 Systems L5 Hymotion

LG Chem, Compact Power, Inc
Inside Structure of Lithium-ion Cells

1. Anode coating, often graphite
2. Anode current collector, Copper
3. Separator, polymeric or ceramic
4. Cathode coating, Lithium metal oxide
5. Cathode current collector, Aluminum

Scanning Electron Microscope (SEM)
Courtesy of Exponent

Nail Intrusion Test
Short Circuiting of Batteries

Chevy Volt, after Crash Test at NHTSA
Real World Accidents

Another Tesla catches fire after 'significant accident' in Mexico (video)

Earlier this week, a Model S traveling at highway speed struck a large metal object, causing significant damage to the vehicle. A curved section that fell off a semi-trailer was recovered from the roadway near where the accident occurred and, according to the road crew that was on the scene, appears to be the culprit. The geometry of the object caused a powerful lever action as it went under the car, punching upward and impaling the Model S with a peak force on the order of 25 tons. Only a force of this magnitude would be strong enough to punch a 3 inch diameter hole through the quarter inch armor plate protecting the base of the vehicle.

The Model S owner was nonetheless able to exit the highway as instructed by the onboard alert system, bring the car to a stop and depart the vehicle without injury. A fire caused by the impact began in the front battery module -- the battery pack has a total of 16 modules -- but was contained to the front section of the car by internal firewalls within the pack. Vents built into the battery pack allow the heated cells to release the heat and vapor from the firewall.
Problem: Internal Short of Batteries During Vehicle Crash

• How much deformation/force a cell can tolerate before reaching internal short circuit?

• Vehicle crashes are inevitable. Often battery packs are also damaged in case of a crash!

• How to design batteries, packs, and vehicle structure to minimize risk of thermal runaway in case of a crash?

• Experimental method?
• Computational tools?

Picture from: http://www.columbiamissouricaraccidentlawyer.com/
Finite Element Modeling as a Tool for Design and Optimization

- Finite element model of batteries for:
  - Identify best electrode/seperator components
  - Choice of cell shell casing (material & geometry)
  - Choice of center core (material & geometry)
  - Design of BIW, pack housing and connections
Summary of Cell Level Testing

Characterization of Mechanical Properties

JPS, Sahraei et al, 2014

JPS, Sahraei et al, 2012
Spherical Tests: Load vs. Time
Constitutive Properties of Jellyroll

From test of compression between two flat plates
Using Principal of Virtual Work

\[ \sigma = A \varepsilon^n \]

JPS, Sahraei et al, 2014
Detecting Short Circuit in Tests

Measuring load, displacement, voltage, and temperature at the same time, short circuit is characterized by:

- Drop in force
- Drop in voltage
- Rise in temperature

Medium Pouch Cell

JPS, Sahraei et al, 2012

JPS, Sahraei et al, 2014
Characterization of Elliptical Cell

\[
P\delta w = \iiint_0^v (\sigma_x \delta \epsilon_x + \sigma_y \delta \epsilon_y + \ldots + \tau_{yz} \delta \gamma_{yz}) \, dv
\]

Assumptions:
- Expansion in Y direction leads to delamination ($\sigma_y = 0$)
- Due to porosity and low Poisson ratio $\epsilon_x \sim 0$
- No binder between layers, free to slide, $\tau_{yz} \sim 0$

\[
P\delta w = \iiint_0^v (\sigma_z \delta \epsilon_z) \, dv
\]

Considering uniform strain in flat section:
\[
A(w) = b(w)L
\]

Inextensibility of shell casing:
\[
b(w) = b_0 + \frac{\pi w}{4}
\]

\[
\epsilon_z = \frac{w}{2R}
\]

\[
P(w) = a(w - h)^n + m
\]

\[
a = 1100, \quad h = 1.4, \quad n = 3, \quad m = 4660N
\]

\[
\sigma_z(\epsilon) = \frac{a(2r\epsilon_z - h)^n + m}{(b_0 + \frac{\pi 2r\epsilon_z}{4})L}
\]
Solving micro equilibrium & calculating macro stresses

\[ \mathbf{P_M} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{bmatrix} = \frac{1}{V} \begin{bmatrix} f_x^{D_1 X} & f_y^{D_1 X} \\ f_x^{D_2 Y} & f_y^{D_2 Y} \end{bmatrix} \]
Failure criterion at various loading scenarios

Failure criterion programmed in RADIOSS (SAHRAEI1)
Finite Element Models

- A model of cell is developed by discretizing geometry into small elements
- Boundary conditions are applied
- Loading conditions are applied
- Material properties are defined
- A software (here: LS Dyna) used to solve partial differential equations of the boundary value problem
- Here for the Battery Model, two parts are defined:
  - Solid element for jellyrolls
  - Shell element for cell casing
Development of macro model

Mat 63, isotropic crushable foam model with erosion option

Three important inputs:
- Compressive stress-strain relationship
- Tensile cut-off value
- Principal strain to failure

Compressive stress-strain:  

![Compressive stress-strain graph]

Tensile cut-off value: 25 MPa

![Tensile cut-off value graph]

Principal strain to failure: a function of loading condition

![Principal strain to failure graph]
Simulation Scenarios

• Compression between two flat plates
• Rigid rod indentation
Comparison of Test and Simulation/ Flat Compression
Validation of Model against Punch Indentation
Hemispherical Punch Indentation
Computational Model of Cylindrical Cell

CT Scans courtesy of Exponent
Uniaxial Tension Testing Procedure

Specimens are Cut Using Templates and an X-Acto Knife

Various Specimens Shown Post-Testing
Uniaxial Tension Testing Procedure

Instron Test Machine Model 5499

Specimen Ready for Testing
Uniaxial Multilayer Tension Tests

Separator Layers (0.025 mm each)
Copper Foil (0.009 mm)
Aluminum Foil (0.015 mm)
CMS Graphite (0.045 mm)
LiCoO$_2$ (0.0925 mm)
Paint Speckle (Size varies)

Comparison of Four Layer Specimen to Summed Individuals

4TH MIT WORKSHOP ON SAFETY OF LITHIUM ION BATTERIES

10/31/2013
Pure Compression Simulation
Uniaxial Loading Scenarios
Failure Mechanism in uniaxial Compression/Tension
Combined Compression/Tension

2 Compression = Tension

Sequence of failure: 1- Aluminum, 2- Copper/Separator, 3- Separator/copper
Fracture Strain a Function of Loading

![Graph showing the relationship between compressive stress and tensile strain ratio.](graph1.png)

![Graph showing the relationship between ratio of compressive strain to tensile strain and failure strain.](graph2.png)
Pack Protection Structures

Studied by Juner Zhu et al
Simulation of Ground Impact

Studied by Juner Zhu et al.
Shield Plate Design

Studied by Juner Zhu et al

- Progressive deformation

Graph:
- Energy absorption (J) vs. Shortening (mm)
- Data plotted with different lines and markers

Diagram:
- Steps of the crash model:
  - Crash starts
  - Ends

Legend:
- ml
- L
- h
- W + H
Summary

• Battery crash response is an important part of battery design for an electric vehicle

• An experimental program using a combination of compression and tensile loading on battery cells and its layered components can be used to characterize material properties of the cell

• Finite element modeling is an effective tool to predict deformation of a battery cell under crash loading

• Finite element modeling is used to predict effect of strength of each layer on average properties of a cell

• Effective design of protective plate can reduce damage to battery cells