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# Deformation and failure mechanisms of 18650 battery cells under axial compression

Juner Zhu [a], Xiaowei Zhang [a], Elham Sahraei [a, b, *], Tomasz Wierzbicki [a]

[a] *Impact and Crashworthiness Lab, Massachusetts Institute of Technology, 77 Massachusetts Ave, Room 5-218B, Cambridge, MA 02139, USA*
[b] *Electric Vehicle Safety Lab, The George Mason University, Nguyen Engineering Building, 4400 University Dr, Fairfax, VA 22030, USA*

## HIGHLIGHTS

- Short circuit happens when an 18650 battery cell is axially compressed to 4 mm.
- Deformation is localized in the positive terminal/endcap region.
- Axial compression of jellyroll creates a circumferential crack in the separator in top region.
- Deformation of shell casing and jellyroll can be simulated by FE model and explained analytically.

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## ABSTRACT

An important deformation mode during ground impacts of battery packs made of cylindrical battery cells is axial compression. This type of loading subjects the cell to a complex deformation pattern and failure mechanism. The design of endcaps plays an important role in such deformations. To explore the sequence of deformation and the underlying failure mechanisms, a combined experimental/numerical study was carried out. Tests were conducted on 18650 cells, and the deformation of each component was carefully investigated and documented. There are four different stages in the force-displacement curve, corresponding with deformation of various components in the endcap assembly. A short circuit happens at a displacement of 4 mm. To clarify these observations, a detailed Finite Element model was set up, covering the geometry and the mechanical property of almost all the components of the cell. Using the simulation results, the sequence of the axial compression was revealed, which was subsequently validated by Micro CT scans as well as analytical solutions. Based on the precise analysis of the mechanical behavior, the cause of the short circuit during axial loading was clarified. Two failure mechanisms in the separator at the top section of the cell explain the possible causes of short circuit.



## 1. Introduction

Cylindrical lithium ion battery cells have been a major power source for Electric Vehicles like Tesla Model S. The vertical configuration of these cells in the floor mounted battery packs make them prone to axial deformation in case of a ground impact. Most of the work on mechanical loading of batteries have been focused on transverse direction for both pouch and cylindrical cells [1–7]. Researchers at MIT Impact and Crashworthiness Lab (ICL) have designed experimental methods to characterize through thickness mechanical propertied of pouch cells under local indentation. They have developed computational models that closely predict response of the cell in such loadings [2,3]. Similar experimental and computational methods were applied to cylindrical cells under lateral loading, by ICL team, and this line of research was followed by Volkswagen researchers [1,4]. Results have also been reported by ICL as well as University of Michigan, on axial loading of pouch cells in which local short amplitude buckling was observed [8–10]. An initial investigation was performed on the Tesla S ground impact accident and it was found that the road debris can produce severe indentation in the protective aluminum armor plate [11]. The computational model predicted a considerable shortening of the cylindrical cells, more than 10 mm, before a sheet separating the battery pack from passenger compartment is punctured. The cells

* Corresponding author. Impact and Crashworthiness Lab, Massachusetts Institute of Technology, 77 Massachusetts Ave, Room 5-218B, Cambridge, MA 02139, USA.

*E-mail addresses:* zhujuner@mit.edu (J. Zhu), zhangxv@mit.edu (X. Zhang), elhams@mit.edu (E. Sahraei), wierz@mit.edu (T. Wierzbicki).

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**Nomenclature**

| | |
|---|---|
| $[\sigma]$ | stress tensor |
| $\sigma_m$ | mean normal stress |
| $\bar{\sigma}$ | von-Mises equivalent stress |
| $\sigma_y$ | yield stress |
| $\sigma_u$ | ultimate stress |
| $\bar{\varepsilon}$ | equivalent strain |
| $\eta$ | stress triaxility |
| $F$ | resistance force |
| $u$ | displacement |
| $p$ | uniformly distributed pressure |
| $R_{out}$, $R_{in}$ | outer and inner radius of shell casing |
| $r$ | radius of battery cell |
| $M$ | fully plastic bending moment per unit length |
| $h$ | thickness of shell casing |
| $E$ | Young's modulus |
| $E_{eff}$ | effective Young's modulus of jelly roll |
| $A_{contact}$ | area of contact |
| $L$ | length of battery cell components |
| $\Delta L$ | deformation of battery cell components |

in that study were previously represented by using homogenized material for all interior of the jellyroll.

Although, the assumption of homogenized material properties works well for transverse loading of cells, it loses much of its accuracy for axial loading, due to special assembly of anode and cathode layers, having a mismatch on top and bottom parts of cylindrical cells. Additional complexity in axial loading is the existence of cell endcap structure at positive terminal. A deformation in axial direction may cause short circuit in the cap assembly well before any failure happens in the interior of jellyroll. In axial loading, a large deformation in jellyroll will lead to local buckling patterns. Such patterns are also detected on compression of laminated and sandwich structures as studied by Karam and Gibson [12].

The objective of this paper is to investigate the modes of failure for various components of 18650 cylindrical cells under increasing axial loading. Deformation and failure in lateral loading cases are more straight forward as it only involves tension and compression of various layers in a continuous uniform way. Axial loading however involves several phenomena in a step by step sequence of deformation for various components arranged in series. Axial deformation, bending, and buckling define different stages of shell casing deformation. Also the jellyroll deformation is non uniform and localized. Mechanisms of short circuit could involve failure in the plastic gaskets, causing contact between shell casing and positive terminal, or failure in separator, leading to contact between electrodes or positive electrode and shell casing.

To identify how the deformation progresses, a detailed finite element model of an 18650 cell was developed. Special emphasis was put on high fidelity representation of endcaps, involving gaskets, safety vent, axisymmetric groove in shell casing, and several other small components. The electrodes and separators were modeled as individual components and a great deal of attention was put on representing the mismatch and interaction between the layers in the top section of jellyroll right under the positive terminal. To represent all the above details, around one million elements were used in the model. The numerical simulation provided a clear picture of the progression of the complex deformation pattern on the upper part of the cell, thus providing a much needed insight about possible causes of short circuit. The predictions were verified by CT-Scan of cells tested in identical loading configurations. It is believed that present results provide great insight for designing next generation of safer cylindrical cells.

## 2. 18650 battery cell

### 2.1. Composition of the cell

An standard 18650 battery cell and its three major components are shown in Fig. 1a. Components include a safety valve at the top of the cell (Fig. 1b), jellyroll (Fig. 1c) and shell casing made of mild steel (Fig. 1d). Safety valves made by different manufactories differ in structure, but commonly several important sub-components are included, such as positive temperature coefficient (PTC) device, aluminum safety vents, steel positive terminal and gasket seal (see Fig. 1e). The jellyroll, which includes anode, cathode and two layers of separator, is the most essential part of the battery cell (Fig. 1f–h). From the structural point of view, the anode is comprised of a copper current collector with active positive electrode material (graphite) coated on its surfaces, and the cathode is an aluminum-film current collector with Lithium metal oxide coating (here: $LiCoO_2$). The separator is a polymeric porous membrane placed between anode and cathode, permeable to ionic flow but preventing electric contact of the electrodes. The separator of the studied 18650 is made of polyethylene (PE) [13].

The basic dimensions of the geometry of the battery cell and its components are carefully measured and listed in Table 1. The readers are referred to the authors' previous publications for more details [1,3,11,14,15].

### 2.2. Material properties of the components

The present research team have devoted great efforts to obtain the mechanical behavior of the individual components of the battery cell, covering elasticity, plasticity and fracture. The properties of the essential components are shown as Fig. 2, including the hardening curves (flow stress-plastic strain) of the aluminum current collector [16] and the copper current collector [3], the engineering stress-strain curves of the separator, the tensile true stress-strain curves of the coating material for anode and cathode [5], and the hardening curve and ductile fracture locus (failure strain-stress triaxiality) of the steel of shell casing [15]. More details about the material properties are reported in the above referenced publications.

## 3. Axial compression test

Axial compression tests were carried out on 18650 cells using a universal testing machine (200 kN MTS) under a loading speed of 5 mm/min (quasi-static range). The setup of the test is shown in Fig. 3a and b. Digital Image Correlation (DIC) method was used for recording the deformation of the cell and the displacement of the loading end [17]. A voltmeter connected to the data-recording system of the computer was employed to monitor the voltage of the cell. The synchronization among the measurements of force, displacement and voltage was realized by computer. All the battery cells were fully discharged before test (SOC = 0).

Fig. 3c presents the results of four compression tests. In three tests both the resistance force (black curves) and voltage (blue curves) were measured. In the fourth one (yellow curve for resistance force), the exterior accessories of the cell (top cover and conductors attached on the positive/negative terminals) had been removed. Results show satisfactory repeatability of the complete cells. However, it should be pointed out that the battery cell is a