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Structural analysis and experimental characterization of cylindrical lithium-ion battery cells subject to lateral impact

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HIGHLIGHTS

- We report on modeling response of cylindrical lithium-ion battery cells to impact.
- The proposed model was validated through experimental testing.
- Two homogenization methods for the jellyroll were developed.
- Experimental results showed a very good agreement with simulations.

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ABSTRACT

We report on modeling mechanical response of cylindrical lithium-ion battery cells that are commonly used in automotive applications when subjected to impact testing. The developed homogenized model that accurately captures mechanical response of a cell to lateral crash is reported. The proposed model was validated using static and dynamic experimental testing. Highly nonlinear mechanical deformations of the cells were captured experimentally using a high-speed camera and later characterized through computer tomography. Numerically, we have investigated the feasibility of using explicit finite element code for accurate modeling of impact on one cell, so it can be used for an entire battery pack that consists of hundreds or thousands of cells. In this study, we have developed and compared two homogenization methods for the jellyroll in a cylindrical lithium-ion battery cell. Homogenization was conducted in a lateral/radial direction. Based on the results of the homogenization, the material model utilizing crushable foam constitutive behavior was then developed for simulations. Experimental results showed a very good agreement with simulations, thus validating the proposed approach and giving us confidence to move forward with the crush simulations of an entire battery pack. Zones of potential electric shortages were determined based on the experiments and simulations.

1. Introduction

Increased usage of lithium-ion batteries in automotive applications makes it necessary to understand their mechanical behavior under extreme loading conditions, such as mechanical impact. One of the key design aspects of any energy storage system, including batteries, is safety, which can be improved by: (a) reducing the probability of an event and (b) lessening the severity of the outcome should an event occur [1]. The current study is part of a project on improving the crash safety of lithium-ion batteries. There have been some studies on failure modes, fault tree analysis, safety and reliability of lithium based batteries [2–5]. In the case of lithium-ion batteries, thermal stability is probably the most important parameter that affects safety in cells, modules and battery packs [6]. Although various safety mechanisms have been implemented in individual lithium-ion cells as well as entire battery packs based on the thermal state of the battery [7,8], there is still a need for better understanding of battery response to extreme loading, which increases a risk of short circuits and the following thermal runaway or fire. One of the biggest challenges in the structural analysis of cylindrical battery cells is a treatment of the jellyroll's mechanical response. A jellyroll consists of hundreds of thin anode, cathode and separator layers wrapped around a center pin. It is a three-dimensional heterogeneous cylindrical structure

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that exhibits anisotropic behavior in axial and transverse directions. This anisotropy can be attributed to the laminated nature of the jellyroll as well as to the fact that the layers in the laminate are not bonded.

Several methods of modeling jellyrolls have been reported in the literature. One way to treat the material behavior of the roll is by representing it as a laminated composite structure. Chatiri et al. [9] did an assessment of the LS-DYNA layered thick shell formulation for thick composite applications to decrease the solution time and still have an acceptable accuracy. However, layered thick shell formulation is not suitable for models with high aspect ratio elements and models including soft materials such as a polymer separator. Classical laminated shell theory [10] can also be used to find the homogenized material response of the jellyroll using a multilinear interpolation of the strain-stress curve [11]. There are two problems arising from using this approach: (1) focus on in-plane properties and (2) inability to account for layers not being bonded, i.e. interlayer slippage. The results obtained using laminated shell theory turn out to be much stiffer than experimentally observed jellyroll stiffness. Kim et al. studied the behavior of small cylindrical lithium-ion cells under abnormal conditions [12]. Compressive characteristics of the jellyroll were assumed to be similar to the separator material, i.e. polypropylene. Various impact and heating tests were conducted on small 18,650 commercial cells with- and without a center pin to determine conditions for the thermal runaway. Greve and Fehrenbach developed a quasi–static mechanical abuse test program with various loading conditions for large 200 mm long and 60 mm diameter cells [13]. They tracked voltage and temperature during the test and realized that when the jellyroll fails, the voltage drops and the temperature increases due to the short circuit. They also developed a finite element model using pressure dependent isotropic Raghava yield criterion as the constitutive model of the jellyroll and applied Mohr-Coulomb criterion to predict fracture inside the jellyroll. Sahraei et al. also performed several experiments on small cylindrical cells (18,650) and recorded voltage and temperature change during their tests [14]. They used stress-strain properties found from the compressive tests on pouch cells as the constitutive model for the jellyroll in cylindrical cells as both cells consisted of the same active materials. Their developed LS-DYNA finite element simulation was based on crushable foam material model as suggested by Sahraei et al. for pouch cells [15,16]. Wierzbicki and Sahraei reported a hybrid, experimental-analytical approach to find the average stress strain properties of the jellyroll in a radial direction with the assumption that the load was carried by a central rectangular part of the jellyroll under the punch [17]. They compared the stress-strain curves of commercial 18,650 cells with the results from pouch cells consisting of the same active materials.

In this investigation, compressive tests on flattened jellyrolls were conducted in order to characterize the stress-strain relation for larger cylindrical lithium-ion cells used in hybrid and electric vehicles. In addition, we have extended the virtual work method of homogenization [17] to larger cells. The experimentally obtained stress-strain curves were incorporated into the proposed explicit finite element models used to simulate crushing cell impact placed between two flat plates. In order to verify the developed FE models, experiments were conducted on cylindrical cells using a custom designed drop test apparatus. For this study, only dry cells have been tested in order to verify the homogenization method and the explicit simulations. However, the method can be applied to "live" cells with electrolyte only if serious safety provisions in place because of the risk of cell explosion or fire. Validation of the proposed approach will help us to get closer to crash simulations of an entire battery pack, which will be used to improve battery design with respect to safety.

2. Jellyroll homogenization

In this study, we have investigated commercially available 6P cylindrical lithium-ion battery cells (3.6 V/6.8 Ah, NCA/Graphite, 140 × 40 mm) manufactured by Johnson Controls, Inc. (Milwaukee, WI), which consisted of four major mechanical components (see Fig. 1): (1) a roll of active battery materials (anode-, cathode- and separator sheets) or a "jellyroll", (2) a center hollow aluminum tube, (3) an aluminum casing and (4) a polyetherimide spacer. The cathode was made of aluminum foil coated with $LiNiCoAlO_2$ active material on both sides. The anode was made of graphite-coated copper foil, and a thin polypropylene separator sheet was used to keep them apart. Modeling each individual layer in the jellyroll during an impact is prohibitively expensive even for one cell, not to mention an entire pack. Thus, our objective was to replace the heterogeneous jellyroll with an equivalent (mechanically) homogeneous material. In order to find the homogenized material properties of the jellyroll, two experimental approaches were considered: (1) a direct compressive uniaxial test of flattened jellyroll samples and (2) homogenization using the principle of virtual work applied to cylindrical samples. The jellyroll material behavior is nonlinear due to the fact that all individual layers forming the jellyroll i.e. anode, cathode and separator, exhibit nonlinear material behavior [17–19]. Therefore, for finite element simulation purposes, a material model has to be derived that accommodates nonlinear stress-strain curves in both radial and axial directions. In this study, an isotropic material model of the jellyroll was considered. The stress strain relation found from the homogenization of the jellyroll will be incorporated in jellyroll's material model in Section 3.3.

The two prevailing impact modes on an individual cell in a battery pack are (1) axial and (2) lateral impacts (see Fig. 2). The focus of this study was on the lateral mode, which would be the dominant deformation mode during a car crash if the battery cells are vertically oriented.

2.1. Direct homogenization using flat samples

We prepared jellyroll samples by cutting an original full length jellyroll into one-inch long cylindrical samples (see Fig. 3a). The samples were then cut in a radial direction and flattened after the inner aluminum tube was removed (see Fig. 3b).

Fig. 4 depicts a flattened sample under compression between two flat rigid plates. Three samples have been tested using an Instron 3369 tension-compression machine, and load–displacement curve was recorded for loads varying from 0 kN to 52 kN (see Fig. 5). It was assumed that only the rectangular area under the plates carried the compressive load. Therefore, stress-strain curve could be easily calculated assuming a constant cross sectional area. Fig. 6 depicts the stress-strain curves derived for the flattened jellyroll samples. The concave-upward shape of the stress-strain

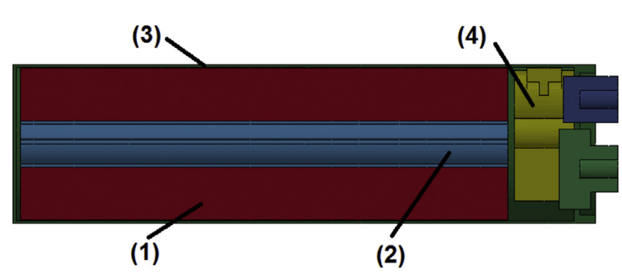

Fig. 1. Cylindrical cell components: (1) jellyroll, (2) inner tube, (3) casing and (4) spacer.