INTRODUCTION

Lithium-ion batteries are widely used in many applications such as consumer electronics, electric vehicles, airplanes, and ships. Recent accidents have highlighted the importance of understanding the behavior of such cells under extreme loading scenarios that may lead to failure and short circuit. The constitutive block of all lithium-ion batteries is electrode layers coated on thin aluminum or copper foils separated by a porous polymeric layer, called a separator. In pouch cells, the sheets of electrodes are stacked, while in cylindrical cells, the multilayer system is wound around a central mandrill. A recent review on the modeling of lithium-ion cells revealed that previous studies have focused mostly on two common form factors, pouch and cylindrical cells and their components. A third type of batteries commonly used in various applications such as electric vehicles is the prismatic cell. The main difference between prismatic and cylindrical cells is the arrangement of electrode-separator layers. Prismatic cells contain a wound system but with a flat section in the center. The central area where the layers locally look stacked resembles a pouch cell, while the sides of the jellyroll resemble cylindrical cells. Because of this special arrangement, characterization of mechanical properties is
not straight forward. For cylindrical cells, Wierzbicki and Sahraei\textsuperscript{27} suggested an approach to characterize the mechanical properties of jellyrolls using the principle of virtual work. For pouch cells, Sahraei et al\textsuperscript{28} presented the methods used for calibration of material properties of large format pouch cells. However, neither of those approaches can be directly used for prismatic/elliptical cells. One approach that can be used for cell characterization is to indirectly obtain the cell behavior at the macro level based on the properties of each constituent layer at the micro level using the homogenization theory. Sahraei et al\textsuperscript{28} conducted tests on individual cell components of a small prismatic cell, designated as elliptical cell, because of the round corners of the shell casing. They developed a 2D microscale layered model of a representative volume element (RVE) in LS Dyna. The sequence of failure at microscale was studied and a failure criterion was proposed. Based on the results of the micro model, a homogenized macro model was developed and validated against experiments using finite element models. What has not been studied yet is the direct characterization of elliptical batteries from cell level experiments. In the present manuscript, this approach is proposed. It should be noted that while elliptical cells are not used in automotive applications, in terms of building block (electrode/separator assembly), they represent large prismatic cells which have wound jellyroll inside a hard metal casing.

Special attention was given to characterization of transverse versus axial loading conditions. As reported in literature, the shell casing, even in the case of pouch cells with thin flexible casing, can have a significant influence on axial response of the cell.\textsuperscript{7} This contribution is even more pronounced in the case of the cylindrical cells with hard metal casing. Additionally, for cylindrical cells, it has been shown that the axial response is controlled by axis-symmetric folds formed at the ends of the cell followed by folds at the center.\textsuperscript{29} Raffler et al\textsuperscript{14} conducted axial compression on 18 650 cylindrical cells and observed that the main deformation occurs at the poles. To the best of authors' knowledge, there is no report of anisotropic homogenized characterization and modeling of elliptical cells, simulating both transverse and axial behavior of the cell. This is one of the main contributions of the current manuscript.

Another focus of the study is on the experimental investigation of the effects of electrolyte on the pattern of failure. Breitfuss (2013) reported similar response of pouch cell components in dry and wet conditions under tensile tests. Tensile behavior of components was used to develop a layered FE model and various loadings were modeled including a compression in axial direction. They reported that the experiments were not reproducible and the FE model was not able to predict the force-displacement curve.\textsuperscript{5} Kisters et al\textsuperscript{30} performed hemispherical punch indentation tests on cells with and without electrolyte, in quasi-static and dynamic regimes and showed significant difference between dry and wet cell responses at high speeds. Therefore, the experiments in this study were performed on both dry and wet cells. A selection of cells was dissected to study the interior failure patterns and identify the contributing factors.

The objective of this paper was to characterize the mechanical response and predict the onset short circuit for elliptical lithium-ion batteries under various loading conditions. Cells with and without electrolyte were subjected to three different loading scenarios including compression between flat plates in axial and transverse directions and hemispherical punch indentation. An analytical approach was suggested and used to characterize and calibrate a homogenized material model for the cell based on flat compression tests in the transverse direction. Subsequently, finite element models were developed and validated with the remaining experiments. Simulation results showed good agreement with experiments in terms of predicting the load-displacement, and the onset of short circuit.

2 MECHANICAL TESTING OF ELLIPTICAL CELLS

Eleven elliptical cells were provided by the manufacturer for testing, including five dry cells with no electrolyte and six cells filled with propylene carbonate (PC) instead of electrolyte. The cells had NCM-Graphite chemistry, and the propylene carbonate was an inert liquid filler used for safety purposes. The cells with no electrolyte and with PC electrolyte are referred to as “dry” and “wet” cells, respectively. Experiments were conducted at the State of Charge (SOC) of 0\%. While SOC of the cell is an important factor in determining the thermal reactions after a short circuit has been initiated, previous studies have shown that SOC does not have a significant effect on the onset of electric short circuit.\textsuperscript{31} In this research, the goal is to predict the initiation of short circuit due to mechanical loading, while the thermal reactions that follow electric short circuit will not be studied here and can only be investigated by thermal and electrochemical modeling of the cell. All elliptical cells had the following dimensions: 63 mm length, 35 mm width, and 18 mm thickness, see Figure 1B. Two types of tests, flat plate compression and punch indentation, were performed on the cells. Flat plate compression was conducted in both the transverse and axial directions, and the punch indentation was conducted using a 12.5 mm diameter hemispherical punch (see Figure 1).

The MTS Loading Frame used for the tests was a displacement-controlled 200 kN machine with a crosshead speed range from 0.1 to 1000 mm/min. The MTS machine was fitted with flat plates for compression tests and hemispherical punches for indentation tests. Testworks\textsuperscript{©} 4 software measured the force and recorded the displacement. An Imaging Retiga 1300i digital camera and Vic-Snap\textsuperscript{TM} and Vic-2D\textsuperscript{TM} digital image correlation (DIC) software recorded and calculated the displacement from marked specimens. In order to ensure safety during full cell tests, an enclosure with ventilation fan and an extension...
rod for the MTS machine were also used. In addition, the wet cells were placed inside plastic bags with SOLUSORB® in case of PC/electrolyte leakage. A RadioShack © 46-Range Digital Multimeter and Meterview software recorded electrical resistance of the elliptical cells. As per findings of Sahraei et al.2,8 in transverse loading, a short circuit coincides with mechanical failure and drop in force. For the axial load cases, a drop in electrical resistance was used to detect the onset of failure. It should be noted that due to safety concerns, the cells were filled with PC instead of electrolyte so that the voltage measurement was not possible. Few tests were repeated with live cells and confirmed that drop in voltage coincides with drop in resistance in axial tests and drop in force in lateral indentation. Therefore, a short circuit can be detected with the above assumed indicators.

2.1 | Compression tests between two flat plates—transverse direction

One dry cell and two wet cells were compression tested in the transverse direction at a rate of 1 mm/min (see Figure 2).

The maximum force was similar for two of the cells, 141 kN for Wet Cell #2 and 137 kN for the Dry Cell. The crosshead corresponding to the peak force was also consistent between these two cells, with a crosshead of 6.7 mm for the wet cell and 6.5 mm for the dry cell. The Wet Cell #1 had a lower maximum force of 118 kN at a crosshead of 6.4 mm.

Following the compression tests, the metal housing was removed from each battery, and the jellyroll was unrolled to view the resulting damage and to determine the type of separator (Figure 2). The unrolled jellyroll of the compressed dry cell had fracture lines in two perpendicular directions, machine direction (MD) and transverse direction (TD), while the jellyrolls of both wet cells had only fracture lines parallel to the MD. The difference in fracture patterns between dry cell and wet cells may be attributed to the coefficient of friction in a dry versus wet environment. In wet cells, with reduced friction, the anisotropy of separator allows movement and stretching in the TD, significantly more than that in the MD. Therefore, failure happens due to high strains in the TD direction with crack line parallel to the MD. In dry cells, high

FIGURE 1 A, Constitutive block of lithium-ion batteries; B, an elliptical cell before testing; C, compression between flat plates in the transverse direction; D, compression between flat plates in the axial direction; and E, hemispherical punch indentation

FIGURE 2 Compression between two flat plates, (A) load-displacement curve; and fracture patterns in (B) Dry Cell; (C) Wet Cell #1; and (D) Wet Cell #2
friction does not allow significant stretching of separator in the TD, and failures in both directions start simultaneously when the underlying isotropic layers of electrodes fail. The separators of the dry cell and Wet Cell #2 were determined to be trilayer polymeric separators. However, the separator of Wet Cell #1, which had lower force measurement at failure, was identified to be a single layer polymeric separator. Therefore, the difference in the peak force of the two wet cells could be attributed to their separator type, considering that the force-displacement curves of the dry cell and Wet Cell #2 with trilayer polymeric separators are almost identical.

2.2 | Compression tests between two flat plates—axial direction

One dry and one wet cell were compression tested in the axial direction at a rate of 1 mm/min. The resistance was recorded during the tests, and the drop in the resistance indicated that a short circuit happened inside the cell. The force level at the onset of short circuit was 6.3 and 5.7 kN for the dry and wet cells, respectively (Figure 3). The load-displacement curve was similar for both cells until the point of short circuit in axial loading which is later shown to coincide with the onset of buckling in the electrode assembly (see Section 3.2). Force continues to increase after this point until reaching a peak and then drops. The dry cell had a maximum force of 10.0 kN with crosshead of 7.0 mm, and the wet cell had a maximum force of 9.6 kN with crosshead of 5.2 mm. Two axis-symmetric buckling folds were observed on the aluminum casing of the cells from outside.

2.3 | Hemispherical indentation tests

Two dry and three wet cells were indented with the hemispherical punch at a rate of 1 mm/min (Figure 4). The three wet cells had lower peak force at the onset of failure compared to dry cells. Postmortem investigations of cells showed that the variation in the response of wet cells may be attributed to the amount of PC liquid in the cells. Wet Cell #2 was observed to have a lower amount of the liquid, while Wet Cells #1 and 3 had more PC content. Therefore, while the addition of electrolyte did not change the trend of force-displacement curves before failure, it did affect the peak load and the onset of failure. In terms of failure location and direction, no significant difference was observed between the wet and dry cells. Both wet and dry cells failed with cracks located under the punch and parallel to the MD direction.

The liquid electrolyte showed different effects in punch indentation and flat compression loading cases. To explain the difference in these two cases, we like to point out that the mechanisms of failure varies as a function of tension to compression loading ratio. Sahraei et al.28 explained that when micro components of batteries are under dominantly compressive forces, such as in case of flat compression, the failure initiation is controlled by metallic components of the cells, that is, current collectors. While, in cases with combined tension and compression, such as hemispherical indentation, the failure is affected mostly by the separator rupture. Mechanical properties of metallic components are not affected by the presence of liquid electrolyte; therefore, in predominantly compressive loads, wet and dry cells exhibit similar failure loads. However, as shown by Sheidaei et al.,32 mechanical properties of polymeric separators are significantly affected by the presence of liquid electrolyte. Therefore, under hemispherical indentation where both tension and compression are applied, and the separator controls the failure outcome, there is a drop in peak force when the liquid is added, and this drop is sharper when amount of electrolyte increases.
3 | MODELING OF ELLIPTICAL CELLS

3.1 | Calibration procedure

In order to calibrate the material model, stress-strain curves in compression and tension are needed. The through thickness compressive curve was calculated from the transverse compression test of the cell between two flat plates (Figure 5). The principle of virtual work was used to estimate the hardening curve from load-displacement curve. In a general loading scenario for a volume, assuming that a virtual displacement of $\delta w$ is applied to object, according to principle of virtual work:

$$P \delta w = \int_0^v \int (\sigma_z \delta \epsilon_z + \sigma_x \delta \epsilon_x + \ldots + \tau_{yz} \delta \gamma_{yz}) \ dv. \quad (1)$$

During compression of an elliptical cell between two flat plates, the curved ends of the jellyroll start to flatten as can be seen in Figure 5. This deformation causes delamination of the layers inside the curved area of jellyroll, which leads to the first assumption that the lateral stress is negligible, that is, $\sigma_z \sim 0$. Due to the porosity of the jellyroll, it can be assumed that the cell length remains constant during loading, that is, $\epsilon_x \sim 0$. The third assumption is based on the fact that the separator is not bonded to the electrode layers and therefore is free to slide in case of shear, that is, $\tau_{yz} \sim 0$. Considering the above three assumptions, principle of virtual work can be written in the following reduced format:

$$P \delta w = \int_0^v (\sigma_z \delta \epsilon_z) \ dv. \quad (2)$$

It was shown by Wierzbicki and Sahraei,\textsuperscript{27} that the strain in the cross section of the cell can be assumed to be uniform in the flattened area of the cell, and can be estimated by $\epsilon_z = \frac{w}{2R}$ hence:

$$P(w) = \int \sigma_z(w) \ dv, \quad (3)$$

and $A(w) = b_w(w)L$, where $b_w(w) = b_0 + \frac{nw}{2}$. Thus, the stress-strain relation can be calculated from the load-displacement curve as:

$$\sigma_z(w) = \frac{P(w)}{b_0 + \frac{nw}{2}}. \quad (4)$$

The load-displacement curve shown in Figure 2 can be fitted by the following expression:

$$P(w) = 1100(w - 1.4)^3 + 4660 \quad (N). \quad (5)$$

**FIGURE 4** Hemispherical punch indentation: A, load-displacement curve; and fracture patterns in B, Dry Cell and C, Wet Cell #1

**FIGURE 5** A, Schematic of deformation under uniform compression, and B, the calibrated stress-strain curves compared to the curve calculated from micromodel and computational homogenization\textsuperscript{28}
Therefore, the stress-strain curve in transverse compression can be estimated by:

\[
\sigma_z(e) = \frac{1100(2R e_z - 1.4)^3 + 4660}{(b_0 + \pi R e_z) L}.
\] (6)

The stress-strain curve in transverse compression is shown in Figure 5B. This curve is compared with the stress-strain curve estimated by computational homogenization of layers of electrode/separator assembly from a micro model of the same cell, reported in Sahraei et al.28 It should be noted that, in the real cell, there are gaps between the layers and between the jellyroll and shell casing. Therefore, a cell model based on the current approach, where all the interior of shell casing (all layers and gaps between them) are considered smeared together in one medium, would have a 17.5 mm thickness. A model based on micro components, as in Ref. [28], only considers the thicknesses of physical layers without any gaps, which results in a jellyroll thickness of 14.5 mm. Therefore, a total gap of 3 mm (or 0.17 mm/mm strain) was taken into account when comparing the two stress-strain curves, which results in the micro model curve start point at 0.17 mm/mm in Figure 5B. The two curves match closely when these differences in characterization approach is considered (see Figure 5).

Lithium-ion cells exhibit anisotropic behavior due to their layered structure (see Figure 1A) as well as the anisotropy of the separator.7,24 Sahraei et al2 showed that the stress-strain curves from in-plane tests was about 9 MPa higher than those from the experiments in the transverse direction for commercially available LiCoO2/graphite small pouch cells. Similar shift in stress-strain curves was reported for LiFePO4/graphite cell and module RVE specimens by Lai et al.33,34 This trend has been attributed to the contribution of aluminum and copper foils to the overall strength of the cell before they reach buckling loads during in-plane loading, when all layers are subjected to equal displacement in parallel. The foils do not affect the overall strength of layers when they are in series with softer layers such as in the case of transverse compression. The 9 MPa additional stress is the critical buckling stress for the jellyroll. Therefore, based on Ref. [2], the cell response in the in-plane direction was estimated by adding a 9 MPa shift to the transverse compressive stress-strain curve (Figure 5B).

3.2 | Finite element modeling

A finite element model for the elliptical cell was developed in LS Dyna. The model contained three parts, shell casing, jellyroll, and endcaps, see Figure 6. Jellyroll was modeled in a homogenized way using 36226 solid elements of 1 × 1 × 1 mm with *MAT_MODIFIED_HONEYCOMB material model (MAT_126). The anisotropic properties in compression were based on the calibration procedure in Section 3.1 (Figure 5). Aluminum shell casing and endcaps of the cell were modeled with 1 × 1 mm fully integrated fast shell elements and piece-wise linear plasticity material model. Properties of aluminum grade 3003-H12, commonly used for lithium-ion battery shell casing, was used to calibrate the material model. The yield stress was 120 MPa. The interface between the jellyroll and shell casing is modeled by eroding single surface contact. Tensile properties were taken from Sahraei et al.7 Maximum tensile strain (TSEF) was used as the failure criteria at which elements erode.

Initially, two loading scenarios were simulated, compression between two flat plates in the transverse direction and indentation with hemispherical punch (Figure 6). Sahraei et al28 previously reported that the tensile strain to failure is a function of compressive to tensile strain ratio, that is, the loading condition. TSEF was set to 0.015 for the case of transverse flat compression (large compressive to tensile strain ratio). For the case of hemispherical punch indentation, a combined state of tensile and compressive strains exists in the cell. Based on the ratio reported in Ref. [28], TSEF was set to 0.03 for this loading. The models successfully predict the load-displacement curves and the shape of deformation as seen from the experiments, in both loading cases (Figure 6). It should be noted that the values of TSEF used in this study are slightly lower than those used in Ref. [28]. This is because the material model used for the cell in the current research is an anisotropic one, while the model used in Ref. [28] was isotropic.

In the next step, the flat compression in the axial direction was simulated. Good agreement was achieved for the load-displacement curves between experiments and simulation up to displacement of about 2 mm, after which the simulation slightly under predicts the load (Figure 6D). Simulation results show axis-symmetric buckle(s) initiated from one end, which is consistent with the experimental observations. A parametric study was completed to verify how the strength of the shell casing may affect the buckling response of the cell by varying σY from 100 to 150 MPa. It can be seen that the value of σY affects the initial buckling force of shell casing. However, after the buckling of casing, the trend and the level of force are similar. Another simulation was completed to understand how much error would be generated if an isotropic model was used for the jellyroll material. This is shown in Figure 6D by the gray dash-dotted line. From this figure, it is evident that consideration of material anisotropy is extremely important for proper simulation of the elliptical battery cell. With an isotropic material model, the strength after 2 mm displacement (onset of buckling of shell casing) would have a significant drop. The anisotropy is due to the additional 9 MPa strength, coming from contribution of aluminum and copper foils in the in-plane direction. It should be noted that the load-displacement curve for the case of axial loading was
filtered using SAE 180 filter. Special attention was made to locate on the curve the point that jellyroll stress level reaches the 9 MPa buckling load. This was found to be at displacement of about 3 mm, which corresponds to the point of resistance drop in experiments. That means the onset of short circuit under axial loads coincides with onset of buckling of jellyroll.

4 | DISCUSSION AND CONCLUSION

A comprehensive experimental, analytical, and computational study was conducted to characterize the mechanical behavior of elliptical lithium-ion cells under various loading conditions. An analytical procedure was proposed to calibrate the through-thickness homogenized material model based on the transverse flat compression tests using the principle of virtual work. The resulting stress-strain curve compares well with that obtained from the 2D microscale model for the same cell previously reported. In order to characterize the cell anisotropy, the in-plane compressive stress-strain curve was estimated by adding a shift of 9 MPa to the through-thickness one. Finite element models were developed and validated for three different loading scenarios. Good agreement was observed between the simulations and experiments in terms of predicting the force-displacement curve. The maximum tensile strain failure criteria were used to predict the short circuit in the cells and was chosen based on the ratio of tensile to compressive strain in the elements. Good agreement was achieved between simulations and experiments in predicting the peak force and corresponding displacement.

Experimental results showed that the propylene carbonate liquid did not have a significant effect on the load-displacement response until the point of failure. This is in agreement with the findings of Gilaki and Avdeev and Dixon et al where no difference was observed in the compressive strain-stress response of the dry jellyrolls or electrode stacks with those soaked in dimethyl carbonate (DMC) or electrolyte. Onset of failure was also not affected by the presence of electrolyte in the case of compression between two flat plates, where layers of electrode-separator assembly

![Figure 6](image-url)

**FIGURE 6** A, Finite element model of elliptical cell with shell casing, jellyroll, and end caps; comparison of load-displacement curve and shape of deformation between simulation and test in B, transverse flat compression; C, hemispherical indentation; and D, axial loading
are predominantly under pure compression. As per Ref. [28] in this type of loading, failure is controlled by the current collector foils for which the mechanical properties will not change under the presence of electrolyte. The wet cells had a slightly lower force than the dry cells at the onset of short circuit under hemispherical punch loading, which is consistent with the results reported by Kisters et al.30 This type of loading produces combined tension and compression, and as per Ref. [28] in this case, failure is controlled by the polymeric separator which according to Ref. [32,36], its mechanical properties have proven to deteriorate with the presence of electrolyte.

Another important factor affecting the peak force is the type of separator. The peak force was higher in cells with trilayer separators as compared to those with single layer separators regardless of the presence of the electrolyte.

In the case of transverse compression, different fracture patterns were observed in cells with and without PC electrolyte, which was attributed to the differences between friction coefficients. In the case of the hemispherical punch indentation, no difference was observed in the fracture patterns between wet and dry cells, both having cracks in the direction parallel to the MD. Sahraei et al.7 reported a similar failure pattern in pouch and cylindrical cells for similar loading scenarios. In these loadings, the separator is subjected to equibiaxial tension in this type of loading and would fail in the weaker direction (parallel to MD), designated as Mode A failure. This is consistent with previous studies of dry processed polymeric separators by Zhang et al.25,26

For the axial compression loading case, no significant difference was observed between location of first peak and onset of short circuit between dry and wet cells. Investigation of stress levels using FE modeling showed that short circuit in this type of loading is coincident with buckling of current collector foils in jellyroll, which again will not be affected by the presence of electrolyte. FE modeling also highlighted significance of considering anisotropic properties of cells when investigating axial (in-plane) loading.

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CONFLICT OF INTEREST

There is no conflict of interest of any kind in the work presented in the manuscript.

ORCID

Elham Sahraei https://orcid.org/0000-0003-4855-032X

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