Mechanical modeling Li-Ion cell crush experiments using LS-DYNA

Matthieu Seulin[1], Charlotte Michel[1], Vincent Lapoujade[1], Pierre L'Eplattenier[2]

[1]DynaS+, Toulouse, FRANCE
[2]LSTC, Livermore, CA, USA

1 Abstract

Electric vehicles (EVs) and hybrid vehicles (HEVs) sales have grown spectacularly in the last few years. Safety has become an increasingly pressing issue in large-format, energy dense Li-Ion batteries used in electric and hybrid cars. The anticipation of the response to abuse conditions becomes an important factor in designing optimized systems. Internal short circuit is one of the most dangerous scenario and has been the root cause of several catastrophic accidents in recent years.

A 3D electromagnetic (EM) model is been developed in LS-DYNA which, coupled with the mechanical and thermal solvers, allows to simulate battery cells in normal use as well as during abusive scenarios when the structure of the battery is damaged (as a result of a car accident for example). The calibration of the already developed electromagnetic model and the establishment of the multi-physics coupling requires the essential mechanical part of the project. In fact, this paper only focus on the mechanical part.

The LS-DYNA software has the technical capability to model the crash of a Li-Ion battery cell as the mechanical, electromagnetic and thermal solvers, are all implemented in the code. The bold part and modeling difficulty comes from the computing resources necessary to run the calculation. In fact, in addition of modeling the multi-physics coupling and the crush using the explicit solver, to model the mechanics of the jelly roll assembly by separately discretizing each of its components implies significantly high computing capabilities for all but very simple problems. Thereby it is fundamental to make appropriate and smart modeling choices and use available options in LS-DYNA enabling to reduce the total computational time while ensuring a correct cell behavior.

Bending and indentation studies have been done to either get results or conclude investigation leads for further work. After dealing with the modeling choices, the study of the global behavior of the cell in bending is presented using periodic conditions to model an infinite plane in the third direction. The effect of the aspect ratio according to the element formulation is at the center of this study.
Then a battery cell model when subjected to a 0.1 mm/min quasi-static imposed displacement indentation test with simplifying assumptions has been done in order to create an indentation model without excessive computation time.

2 Introduction

Electric vehicles (EVs) and hybrid vehicles (HEV) sales have grown spectacularly in the last few years. Safety has become an increasingly pressing issue in large-format, energy dense Li-Ion batteries used in those cars. Among various abusive scenarios for Li-Ion batteries, internal short circuit is one of the most dangerous and has been the root cause of several highly catastrophic accidents in recent years.
The failure of lithium-ion batteries can be due to various external or internal abusive conditions where the mechanical-abuse-induced short-circuit is a major problem. A battery crush is a multi-physics phenomenon: the mechanical aspect is the crush; the electrical aspect is the short circuit and the thermal aspect is the short-circuit consequence. Computational models are an efficient way to study multi-physics algorithms and provide insights to the design of safer Li-Ion batteries.

2.1 The pouch cell modeling

The pouch cell internal structure is made from repeated layered structures of positive electrodes (cathodes), separators and negative electrodes (anodes) that can be folded or coiled in different patterns. Electrodes consist of a layer of metal (Al, Cu) foil (current collector) usually covered on both sides with active material. The active material is very porous and saturated by electrolyte. The layers

are planar sheets with length and width of up to tens of centimeters and thicknesses of the order of micrometers.
The Ford – LSTC collaboration has developed a specific 3D electromagnetic (EM) battery model. This model has been coupled with simplified mechanical-thermal model to validate the multiphysical behavior. Then, once a realistic mechanical model is developed, it will be coupled to both thermal and EM solvers in order to simulate battery cells in normal use as well as during abusive scenarios when the structure of the battery is damaged [1]. Since the cell mechanical behavior is the main modeling difficulty of the project and necessary for the calibration of the electromagnetic model, the focus of this paper is on the mechanical part.

2.2 Mechanical modeling difficulties

The mechanical response of the battery cell internal structure (called jelly roll) is still not well understood. The project requires to model crush experiments using explicit solver, in particular model the mechanics of the jelly roll assembly by separately discretizing each of its components which imply significantly high computing capabilities for all but very simple problems.
Taking into account the layers thicknesses, a cell model with 3 elements in the thickness of each layer and with a ratio aspect equal to 1, would require 228 billion elements. Moreover, the size of the elements in this model must be of the order of several micrometers which would greatly diminish the time step. In addition, during the indentation test the elements are compressed and their thicknesses are then reduced. As a result, the time step decreases over time.

The combination of all these features shows that obviously, it is not feasible using an approximative 15 x 20 cm cell when complete vehicles are constituted of only several million elements of the order of a few millimeters. Thereby it is fundamental to make appropriate and smart modeling choices and use available options in LS-DYNA enabling to reduce the total computational time while ensuring a correct cell mechanical behavior.

2.3 The study approach

The mechanical study and modeling of the cell subject to crush experiments can be separated into two parts. The first concerns the behavior of the battery away from impact where the only relevant mechanical stress is the bending one. This deals with the use of the best element formulation according to the aspect ratio variation on 3 points bending simulations. The aim of this approach is to find the best time saving while ensuring a correct cell mechanical behavior.
The second step of the approach is the behavior of the battery at the precise location where the cell will be impacted where the relevant mechanical stresses are mostly compression and shear stress. There is some interesting work with representative sandwich (RS) models [2, 3, 4] which validate that using a single RS can simulate reasonably well the mechanical response of a full pouch cell during indentation tests..

3 Global bending behavior study

3.1 Finite element formulation comparison

The first step of the project is to determine which element class is the best to simulate our physical system i.e. regarding the final purpose which is simulating compression of stacked thin layers.
In the simulation of thin-walled structures, Belytschko-Tsay and Hughes-Liu shell elements are widely used [5]. However, in some cases thick shell elements (tshell) or solid elements are more suitable. In our case, thin shell elements cannot give satisfactory results because shell elements cannot give us relevant strain information through the thickness.

3.1.1 Numerical model

All the models in this section will be 3-points bending models. Indeed, far away the indentation punch in the cell, the only relevant mechanical stress is the bending one. Since the material choice does not influence this sensitivity study, steel and then *MAT_PIECEWISE_LINEAR_PLASTICITY has been considered. The contact friction is unknown and has been chosen equal to 0.1 (leave the default value 0 would not be realistic). Given its plan of symmetry, only half of the models are represented (see Fig. 1). A vertical displacement is imposed at 1 e-4 m/s with a total displacement of 100 µm. Although the

loading speed is much higher than the one used in a typical quasi-static experiment, the simulations are still considered quasi-static since the kinetic energy represents less than 1% of the total energy [4]. To reduce the computation time in this study, a modeling technique called “false 2D” will be used which means the bending plate is modeled with only one solid or tshell element through its width, making it looks like a beam. However, two parallel symmetry planes are situated along the “beam” sides acting like two mirrors. This allows to simulate an infinite (in its width direction) bending plate instead of a bending beam.

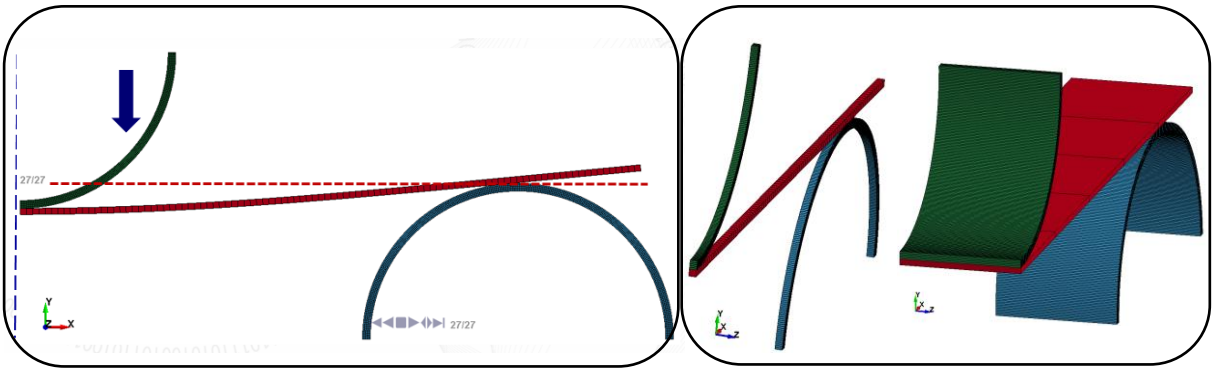


Fig.1: Mesh of the 3-points bending simulation for the finite element formulation study (particular case with one element through the thickness). Side view on the left. On the right, the aspect ratio is highlighted with the width difference between models)

The main varying parameter in this work is the aspect ratio. Indeed, considering the significant computation time, studying the possibility of increasing the aspect ratio far away from the indentation location (and by how much) is a requirement. Besides the aspect ratio, there are three varying parameters in this study:

- The first one is the model width, depending on the wanted element ratio aspect to ensure squared elements in-plane.
- The second parameter is the number of elements through the thickness (NET). It can vary from one to three. Then the element aspect ratio also depends on the NET. For example, for the model with 5 elements along the length, if NET equals to 1, 2 or 3, the aspect ratio is 20, 40 or 60 respectively. Because modeling thin parts require the use of several elements in the plane to maintain accurate bending behavior [6], 5 elements are the minimum number along the length in this study.
- The third parameter is the element formulation. Tshell 3, 5 and 7 were tested and solid 2, 3, -1 and -2 were tested.

There are no experimental data for this 3-points bending study to compare our simulation results with. However, the classical beam theory gives:

$$\frac{R}{W} = 4uE\frac{T^3}{L_r^3}$$

where R is the resultant force, u the deflection, E the Young’s Modulus, W the width, T the thickness and Lr the length between rods.

In this study, the width depends on the aspect ratio and is not the same for all models. That is the reason why we are using the nondimensional theoretical resultant force (without friction) as reference value. This value is however not completely realistic as it does not take into account friction, which should not be neglected. The numerical model considers some friction and its resultant force is then expected to be higher than the beam theory value.

3.1.2 Results and discussion

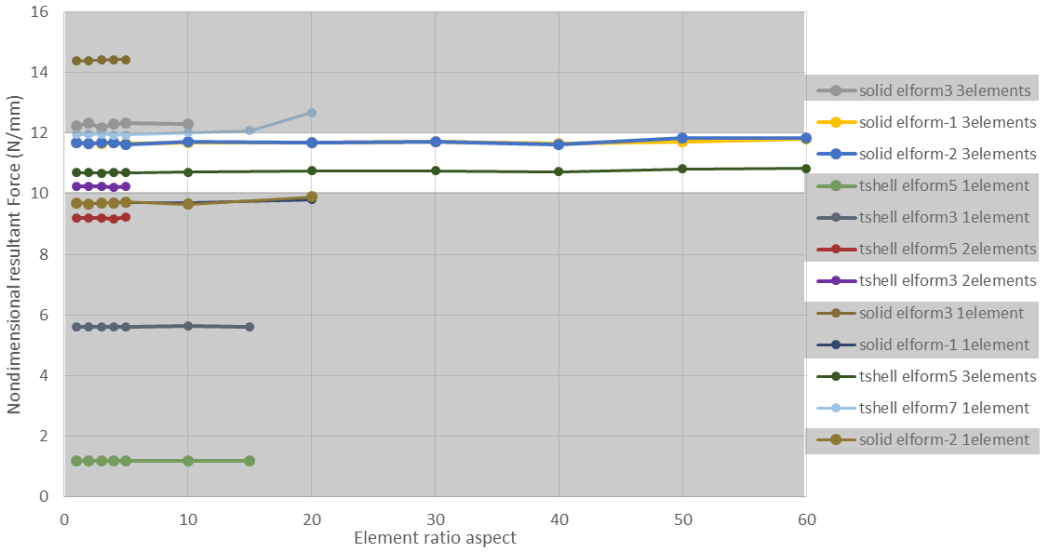


Fig.2: Element aspect ratio study on 3-points bending simulation. Resultant force comparison between element formulations

Fig. 2 presents the results of the study first part. For each element formulation the curve of the evolution of the nondimensional resultant force versus the element aspect ratio has been plotted. There are 98 points and each point on the graph represents a simulation. There are 14 different curves coming from the eight studied element formulation combined with a varying number of elements through the thickness.

An observation is that, even for a same aspect ratio, all the nondimensional resultant force are not equal. This means that some element formulations used with a certain number of elements through the thickness are not suitable to properly represent a bending behavior. To determine which formulations are accurate or not and then which one to keep or eliminate a trust interval of resultant force is defined (see Fig. 2). To build the trust interval, two bounds are needed. The lower bound is determined thanks to Eqs. (1). The upper bound is chosen thanks to solid ELFORM 2, and 2D solid formulation 13 with 4 integration points because their results can be trusted in most cases, for an aspect ratio equals to 1. All element formulations outside this trust interval are eliminated.
There are then three remaining element formulations. Since only one is needed to model our system, another selective very important criterion is required. This criterion is the computation time.

Few observations can be made about Fig. 3. First of all, in term of computation time, solid ELFORM -1 with NET=3 and tshell ELFORM 5 with NET=3 are equivalent. However their resultant force is not the same and tshell ELFORM 5 seems to be not stiff enough compared to the solid formulation. These models were conceived with frictional contact which explains a greater resultant force than the classical beam theory prediction. Moreover, one of the best interests in using tshell elements is their theoretical capability of needing only one element through the layer thickness, so to reduce the total number of elements in the model (and increase the minimum time step). According to Fig. 3 the tshell ELFORM 5 needs 3 elements through the thickness to give a rather good resultant force. As a consequence solid ELFORM -1 will be preferred between these two formulations.

Regarding tshell ELFORM 7, with only one element through the thickness, it is the best formulation in term of computation time and it gives a quite accurate resultant force result. It looks like the best candidate to model our system. However indentation simulation tests have been performed with this formulation and have given wrong results. The tshell ELFORM 7 is really recent and there is still some work in progress on it, probably the reason why it still does not appear in the LS-DYNA manual. The problem encountered has been shared with LSTC and its developers are working on it. Consequently, knowing that tshell ELFORM 7 with 1 element through the thickness does not work for now for the indentation tests. Solid ELFORM -1 with 3 elements through the thickness has been chosen to model the cell.

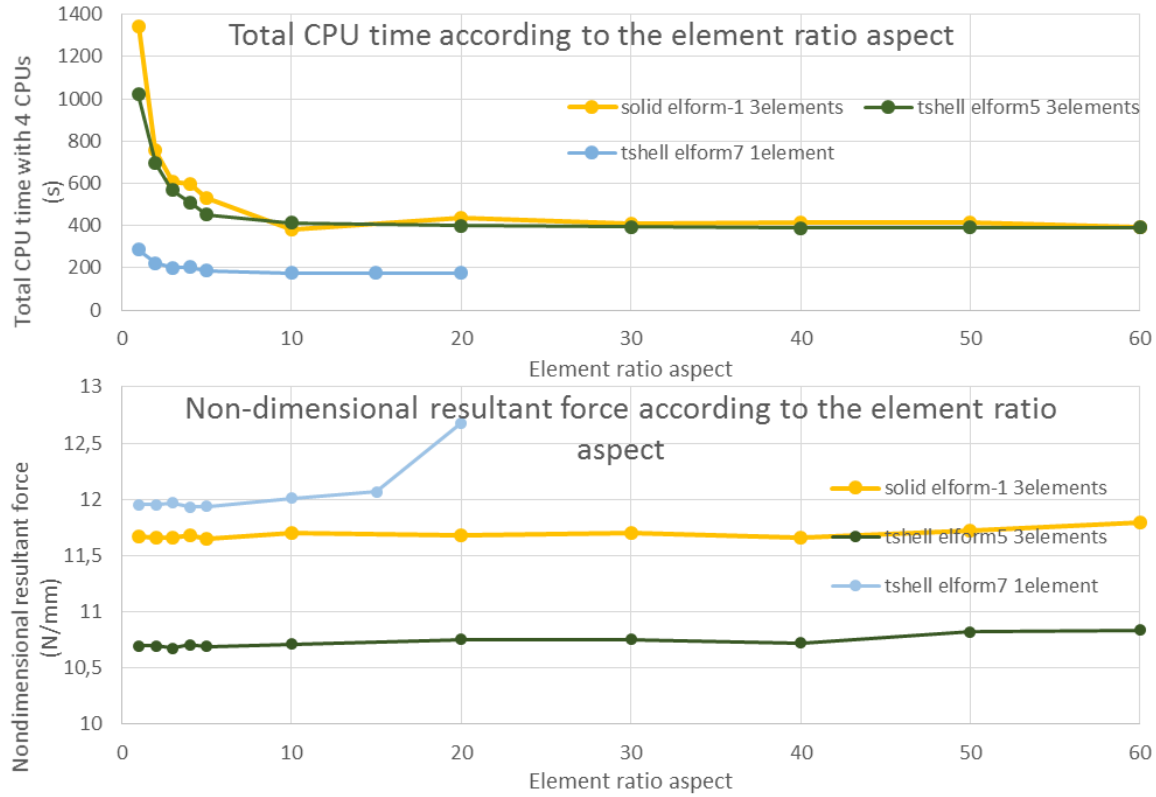


Fig.3: Three finalist element formulation after sorting out those which gave unsatisfying results on 3-points bending simulation. Total CPU time and resultant force over the element aspect ratio

3.2 Bending of the complete cell

3.2.1 Numerical model

Now that the most suitable element formulation has been determined (solid ELFORM -1), an aspect ratio sensitivity study on the complete cell is required. 3-points bending simulations of the complete cell in “false 2D” are run with different element aspect ratio in order to determine by how much the aspect ratio can be increased while maintaining accurate results. The objective is to be able to reduce the total number of elements in the final battery cell model.
Regarding the material point of view, the content of the cell is structurally anisotropic. However, all the components of the jelly roll (Cu and Al current collectors, electrodes active materials, and separator) are isotropic.
In previous works [2, 7], it was suggested that the current collectors can be modeled using the piece-wise linear plasticity representation in LS-DYNA.
The mechanical responses of the active material layers and the separator are more complicated due to the presence of porosity. The Poisson’s ratio in these materials is assumed to be zero since no transverse deformation is observed under compression. Compressible foam has been used in the literature to describe the basic properties of these layers [3, 7, 8]. Series of experiments were performed by Ford for this project in order to characterize the tensile and compressive properties of the active materials (anode and cathode) and the separator which was used to fill the **`*MAT_CRUSHABLE_FOAM`** cards.

Fig. 4 presents a schema of the model mesh for this study. The model thickness is made of stacked layers. A sequence called the Representative Sandwich (RS) is repeated 16 times through the thickness with an additional anode and separator at the bottom. The infinite plane simulated by the symmetry planes in the third direction (false 2D assumption) is corresponding to the plane in the real battery cell which has the biggest length. The cell is contacted along its centerline with a 5 mm diameter cylindrical indenter, and is supported at a distance of 11.6 cm (from the contact line) by two 5 mm diameter rods.

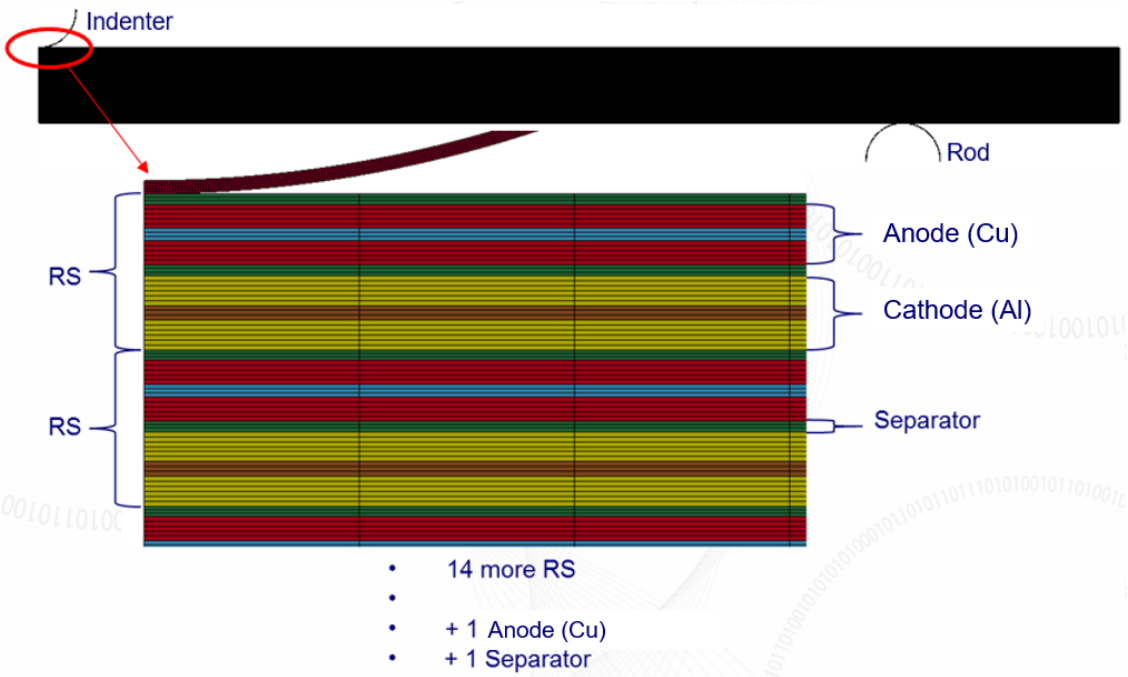


Fig.4: Mesh of the 3-points bending simulation on the complete cell for the element aspect ratio with element formulation solid -1 (particular case of the ratio aspect = 20)

The smallest characteristic length in the model is the thickness of a separator element which is 6.67 µm (see Table 1). In fact, three elements through the layers thickness are required to calculate accurately the bending stiffness. According to the layers thickness, the model time step is very small. As a result, making a reference model with an element ratio aspect equals to 1 is not possible in term of computation time. The previous study has shown that an aspect ratio equals to 60 gives good results with solid elements ELFORM -1. Finally, the lowest affordable aspect ratio, considering the computation time, is decided to be 20 and the corresponding model is taken as the reference one. The aspect ratio then varies from 20 to 600 passing by 40, 60, 100, 150, 200 and 300 in order to determine what the greatest eligible aspect ratio is.

Layer	Mesh color in Fig. 4
Separator	Green
Anode active	Red
Anode collector (Cu)	Blue
Anode active	Red
Separator	Green
Cathode active	Yellow
Cathode collector (Al)	Brown
Cathode active	Yellow

Table 1: Recapitulative table of the Representative Sandwich sequence (RS) which is repeated 16 times through the battery thickness

3.2.2 Results and discussion

Fig. 5 presents the nondimensional resultant force versus the deflection for models with aspect ratios from 20 to 200. Models with 300 and 600 aspect ratios give unsatisfying results. The observation that all curves present instabilities can be made. This can be explained by the following reasons:

- The model geometry is suitable to instabilities owing to the great length of the model (compared to its thickness). Moreover the model is not homogenized with its 132 stacked layers of different materials,
- The materials stiffness is very low,
- Numerical simulation is an approximation of the physical behavior. Numerical instabilities might be added to physical instabilities.

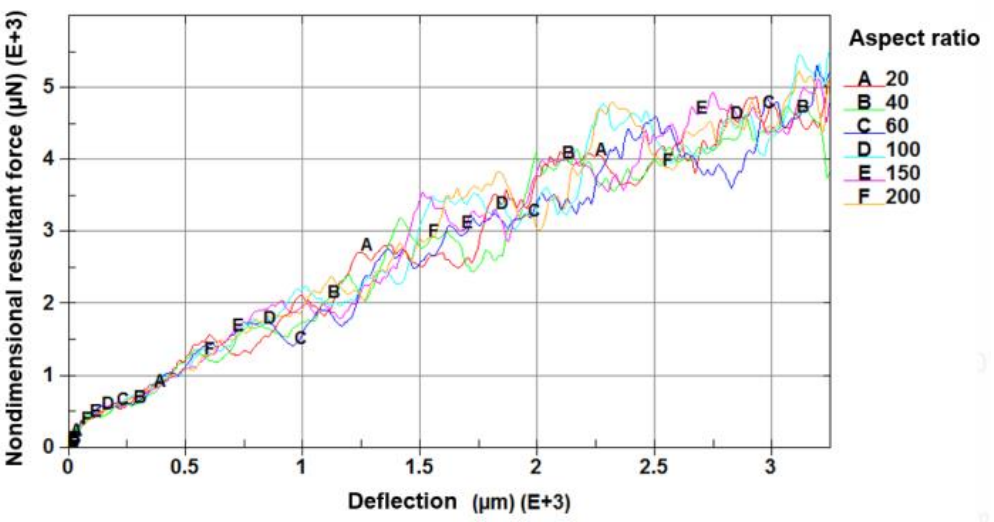


Fig.5: 15 points floating average on the structural response of the complete cell with one element through the width on the 3-points bending simulation

The floating average allows to see that all these curves have the same linear tendency, which is normal as the varying aspect ratio should not change the resultant force result. So even if experimental results and theoretical calculations are not available to validate this simulation, we can afford to say that the consistence between all these curves indicates the proper response of the model. Therefore, solid ELFORM -1 can be used with aspect ratio up to 200.

In term of computation time, the model with a 20 aspect ratio takes the substantial 35 hours to run on 28 CPUs which explains why a model with an aspect ratio of 1 cannot be an option. The model with a 200 aspect ratio takes 5 hours on 28 CPUs which divides the total computation time by 7. This result is very significant for the following.

4 Indentation behavior study

The purpose of this section is to model the battery cell mechanical behavior when subjected to a 0.1 mm/min quasi-static imposed displacement indentation test.

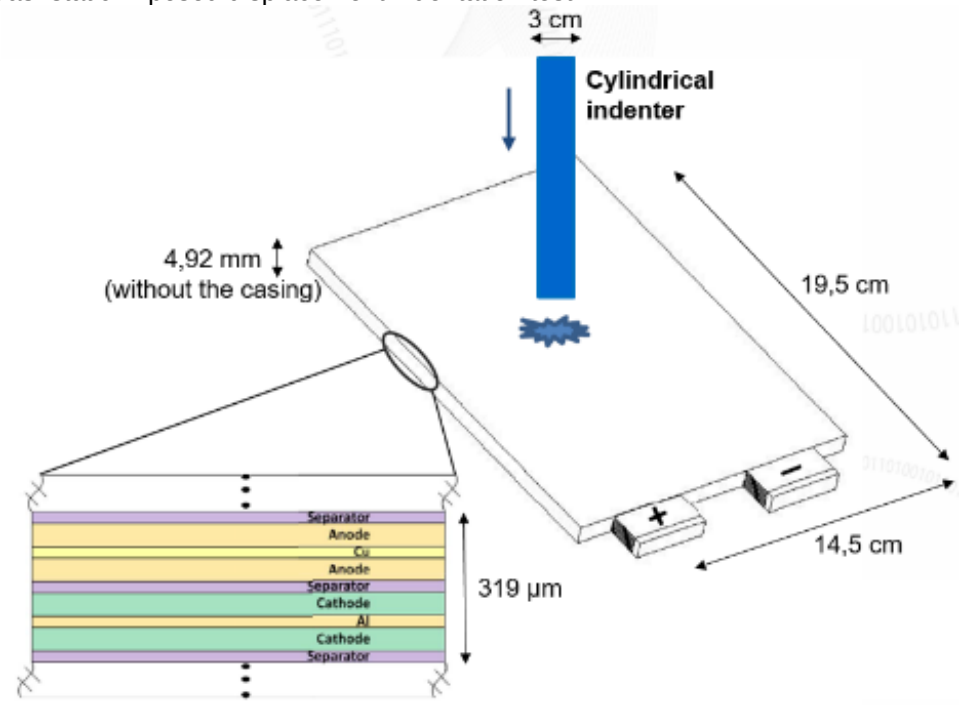


Fig.6: Schematic representation and dimensions of Ford experiment indentation tests

Even with the computation time reduction determined in the previous part, the gain is not enough to simulate the battery cell indentation (with every layers modeled) without huge computing capabilities for the following reasons:

- The optimized bending simulation with a 200 aspect ratio takes 5 hours to compute on 28 CPUs. During a compression simulation, the model time step decreases with the elements thicknesses. As a result, the more compressed the cell is, the lower is the time step and the greater is the computation time.
- The optimized bending simulation does not need a refined mesh impacting cylinder zone. In the compression simulation, refining the mesh around the indenter is important to get a correct structural response and avoid contact. To refine the mesh around the indentation zone (and make a mesh bias from the indenter border to the model border) substantially increases the total number of elements in the model and also the computation time.
- The simulations made in Section 2 are in “false 2D”. In the compression simulation, it is not possible to use the “false 2D” method because of the indenter cylindrical shape. Consequently, the total number of elements in the model would be approximately multiplied by 100. Finally the computation time would significantly increase.

The combination of these three reasons allows to say that with a reasonable number of CPUs, the computation time of the battery cell indentation simulation is not affordable. Then it is essential for the moment to find modeling tips which will enable the reduction of the computation time.

4.1 Model presentation

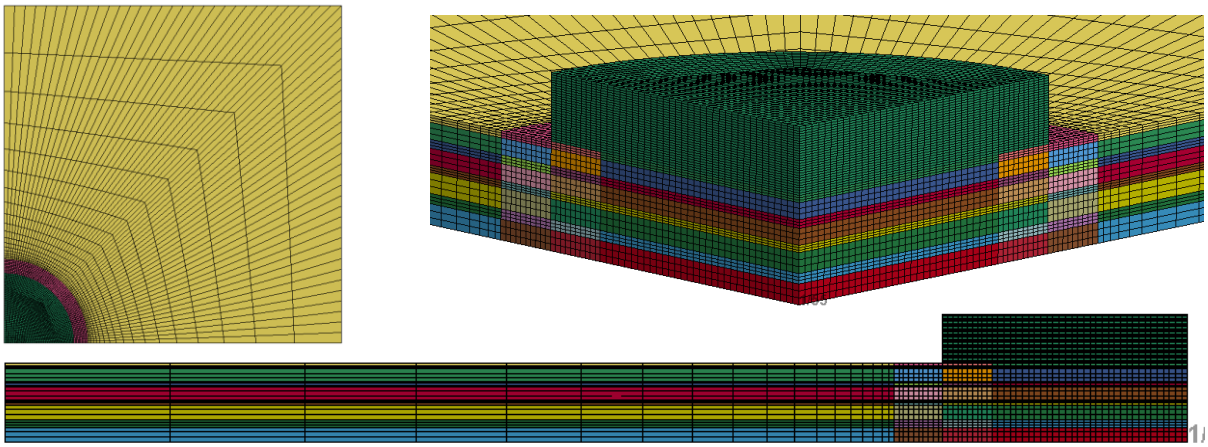


Fig.7: Three different views of the mesh used for the indentation study

The model composition is presented in Fig. 7. This model is inspired by C. Zhang’s model [4] but not with the same representative sandwich sequence as C. Zhang chose a representative sandwich made of only five stacked layers. It was preferred to take the representative sandwich sequence previously defined because in our option this choice better represents the cell internal structure.

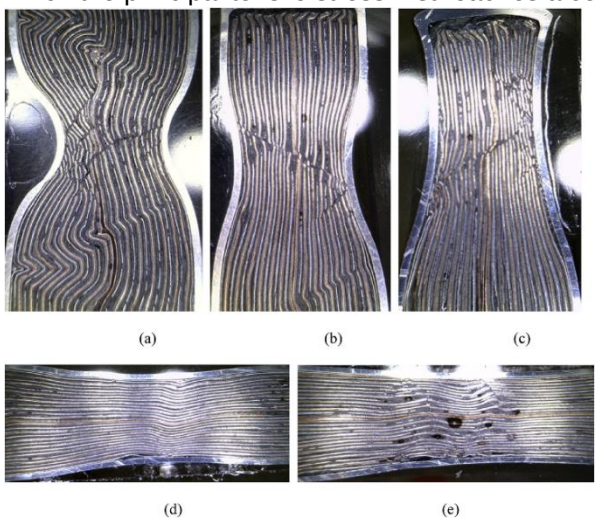
Since the model has two planes of symmetry, we only consider one quarter of the (actual in-plane) domain in our finite element model, so to save computational time. The cell edges are left free. Nodes in the x0z symmetry plane are fixed in y-displacement and x and z-rotations. Nodes in y0z symmetry plane are fixed in x-displacement and y and z-rotations. The bottom surface of the battery model is simply supported on a rigid wall. The casing is not considered in this study, since its contribution to the mechanical response or the initiation of the court-circuit can be isolated from the response of the cell components as reported by Sahraei et al. [7]. The indenter is a 3 cm diameter cylinder modeled with solid rigid elements. The indenter is moving downward in the z-direction at a constant speed of 0.4 m/s. Although the loading speed is much higher than the one used in a typical quasi-static experiment, the simulations are still considered as quasi-static since the kinetic energy is less than 1% of the total energy [4]. The contact friction is unknown and has been chosen equal to 0.1 (leave the default value 0 would not be realistic).

On the model edges, far away from the indenter the element aspect ratio is approximately equal to 200. There is a progressive mesh refinement towards the indenter where the aspect ratio is around 3. This allows to reduce the total number of elements in the model, equals to 130,000. Also the mesh geometry of the cell is optimized such as to fit the indenter shape. Indeed, a nodes line is created under the indenter in order to coincide with its edge. Moreover, since in Fig. 8 most of the deformation and failure occur under the indenter edges, two rings are created on each side of the node line with a refined mesh. These two rings will permit to better capture the deformation at these locations.
The nodes that make the joint between two superimposed layers are merged. This simplifying assumption justifies the use of this model to approximate the entire cell behavior. In fact, in the full cell, the stiffness of each layer is added to the others in series. Then, during compression loading it is possible to approach the total stiffness (sum over every layers) by using an appropriate stiffness for each of the eight layers of the approximate model. This is only possible if the nodes between layers are merged.

4.2 Study

4.2.1 Experimental observations

In references [7, 8, 9, 10], it was observed through experimental measurements of the cell voltage that the moment at which the voltage drop occurs correlates with the moment at which the mechanical failure of the battery structure is observed. Through thickness stress components initiate fractures at the surface and induce shear failures in the active material layers. Fig. 8 shows fractures at the surface of the pouch under the indenter around its boundaries but the failure does not obviously initiate at the surface. Then it is essential to study the mechanical failure of cell internal layers. Moreover, in indentation tests the short-circuit initiation was assumed to be located along the same coordinates at which the principal tensile stress first reaches a certain magnitude [8].



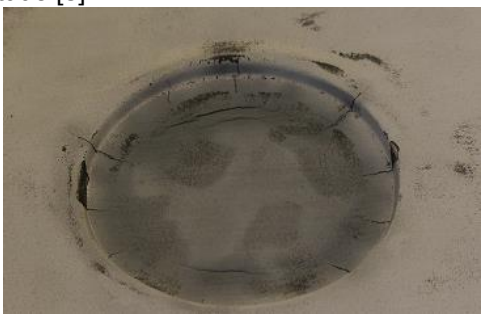


Fig.8: Internal configuration of the cell deformation at the onset of short during compression tests (to the left). External view of the cell deformation at the onset of short during indentation tests (to the right)

One of the purpose of this section is to accurately simulate observations made by Ford research team and Srdjan Simunovic and his team from ORNL which are:

- Micro-buckling appeared in the cell internal structure under various compressive loading conditions on dry Graphite/LiFePO4 cells (see Fig. 8),
- Failures appeared under the border indenter (see Fig. 8),
- Internal short circuit appears between 53 and 60 % of strain.

The purpose of this section is also to find a numerical erosion criterion which verifies experimental observations:

- A short circuit occurs during indentation tests, due to some cell failures. Then in the finite elements model, erosion should appear. The cell final state (when the indenter displacement reaches the interval [2.9 mm – 3.3 mm] for which the short circuit happens during the experiments) could then help to find a criterion triggering the EM short circuit.
- Neither short circuit nor failure occurs during bending tests. Then there should not be any finite element eroded in the cell bending simulations.
- No failure and no short circuit were observed for compression between two flat plates [8].

It means that is the indenter border (whatever the indenter radius when there is one) which induces the failure in the cell. Then the criterion must permit to erode only sheared elements located under the indenter border where the tensile criterion is reached.

4.2.2 Numerical failure criterion

Simulation of cell components mechanical failure has rarely been reported in the literature. To model mechanical failure, one must consider deletion of elements when achieving a defined failure criterion, such as a stress or strain value.

The criterion studied and probably the best is the one based on the minimum pressure at failure. It is the only one which allows to isolate the tensile component of stresses (pressure is the same dimension than stress). Moreover, the definition of the criterion can be easily made separately for both active materials and the separator which means the three materials can erode with their own criterion. C. Zhang did not make the same choice and focused on the separator erosion only [4]. However according to Ford's experiments, the cathode active and the anode active failed in tension before the separator. Then erosion will be considered on the three materials.

The Tensile Cutoff parameter (TSC) shows that the separator is not the one which fails first during a tensile test. A special characteristic of the TSC which has not been specified yet is that this parameter value depends on the mesh size. Moreover, the material behavior depends on this parameter. The smaller it is, the less stiff is the material. Right now, no data can help to calibrate this parameter for the chosen mesh which is why the average value of the failure in tension has been taken as the TSC value. That same TSC value is chosen as the criterion value for each material. This choice has been made because both parameters (TSC and pressure criterion) have the same dimension and because it seems like a sensible value to start with. It quickly appeared that it was not a bad choice because enough erosion appeared in the first simulations with this value of the criterion. This initial value has allowed to start working. This sensitivity study is not complete because of some difficulties encountered during the internship which are specified in the next section. Once these problems are solved, the study of the criterion should continue.

Meanwhile, a 3-point bending model has been set up to check that the two mechanical observations defined in the previous section are fulfilled with this erosion criterion (erosion during indentation tests but not during bending tests). It contains 75,000 elements and run for 365 hours on 28 CPUs to cover 6706 micrometers. The results of this simulation show no eroded elements in the model. Then this criterion is worth keep working with as it is likely to give satisfying results in the future.

4.2.3 Current state of the results

The materials used apart from the current collectors have a low stiffness. Attention should be paid to contacts involving these materials to ensure good behavior. Because of their low stiffness, these materials are predisposed to undergo large deformations leading to elements inversions (negative volume). This happens when the material behavior curve is not defined over a large enough interval and has not been stiffen at its end. In fact, since LS-DYNA extrapolates the material curves once it gets to their ends, there are some cases when it can lead to more than 100% of deformation, which is not realistic. The curves final slope then should be increased. However, in our case, it would not be a really judicious choice. In fact to stiffen the behavior curves would reduce the time step and increase the computation time (explained in Section 1.1.2). Another numerical solution exists to prevent the generation of negative volumes. It consists in using a stiffness factor of 10 for the elements with thicknesses below 10% of its initial value, during indentations simulations (*CONTACT_INTERIOR).
Sometimes, when there are very high levels of compression like in our model, this numerical solution is not sufficient to prevent the creation of negative volumes. An option called "PSFAIL" is available in LS-DYNA to check the specified part set for negative volumes and erode inverted elements. Enabling PSFAIL is not in the interest of this model as it might lead to unrealistic material failure. However, in many cases it can be very useful to prevent the calculation to stop unexpectedly because of negative volume.

During all the project study, the indentation model has been subjected to some penetrations issues between the indenter and the battery cell. Fig. 9 presents an example of the penetration problem encountered.

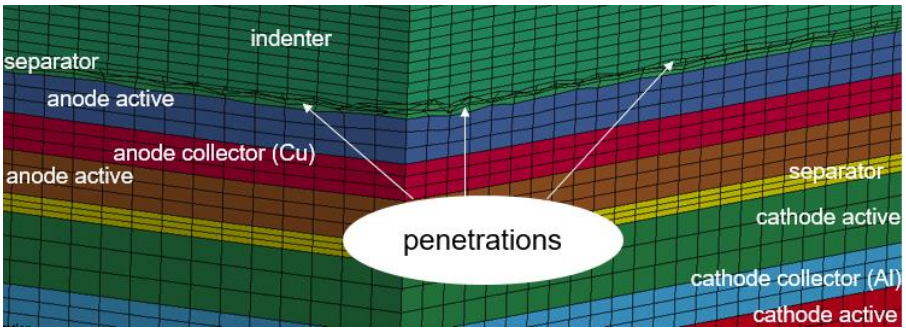


Fig.9: Highlighting of penetrations in local indentation study

The indentation study is still in progress. The priority is then to find a work around the penetration problem. Fig. 10 presents the deformed shape of the final model. The erosion criterion is used only for both rings under the indenter edge as it is where failure is expected to happen in first. Both models stop with an error termination ending. The computation time is between 5 and 10 hours with 28 CPUs depending on the contact used.

A penalty contact is used. On one hand, the contact is not very well handled and penetrations are observed. On the other hand, micro-buckling appear like in ORNL's experiments (Fig. 8) which is encouraging.

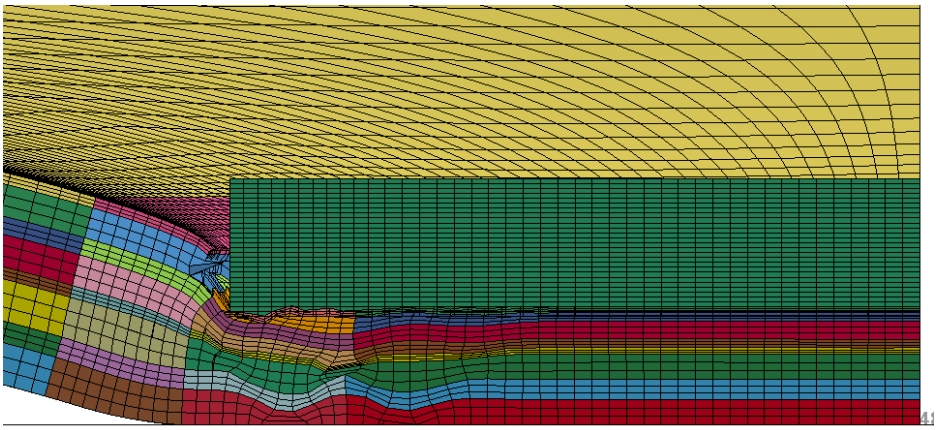


Fig.10: Deformed shape of the model at the final stage of the indentation before error termination. Side view

The final displacement of the indenter is equal to 2.6 mm and the cell thickness reduction gets to 54%. During Ford's experiments, the internal short circuit appears for an indenter displacement between 2.9 and 3.3 mm which corresponds to a thickness reduction between 53 and 60%. The models results are then encouraging for further work.

5 Summary

The objective of this project was to focus on the mechanical modeling of a Li-ion battery cell crash in order for Ford to later create a multi-physical model with mechanical-thermal-electromagnetic coupling. Many studies have been done to either get results or conclude investigation leads for further work.
The LS-DYNA software has the technical capability to model the crash of a Li-Ion battery cell. The mechanical, electromagnetic and thermal solvers, are all implemented in the code. The modeling difficulty comes from the computing resources necessary to run the calculation. Find modeling tricks is then essential to be able to model this phenomenon without excessive computation time. Several ones have been used in this study such as to use periodic conditions to model an infinite plane in the third direction or use mass scaling to increase the model time step. Also to approach the behavior of the battery by modeling the sequence that is repeated through the thickness scaled at the real battery thickness or to maximize the aspect ratio of the elements so to reduce the number of elements in the model.

This work also allows to conclude that the use of the element formulation solid -1 is the most suitable to represent the cell bending behavior and the most advantageous in terms of computing time. It is used outside the area under the indenter and with a large aspect ratio going up to 200 which significantly reduces the number of elements in the model.
Final conclusions are about the search of a numerical erosion criterion. On one hand, this criterion should not lead to any finite element eroded in the cell bending simulations. On the other hand, during indentation simulations when the tensile components of the stresses exceed a defined limit value in finite elements, these elements should be eroded. As a result, eroded elements should be located through the battery thickness under the indenter edge where the tensile criterion is reached.
Improvements regarding the ELFORM tshell 7 have been done recently by LSTC in order to accurately calculate the battery mechanical behavior with time saving. Moreover LSTC has developed a new promising element formulation of composite thick shells. This will be studied and may be another work lead for battery modeling purposes.

6 Acknowledgement

James Marcicki, Jie Deng and Chulheung Bae from the Ford Research and Innovation Center of Dearborn, MI, USA are acknowledge for the help provided.

7 Literature

[1] Pierre L'Eplattenier, Iñaki Caldichoury, James Marcicki, Alexander Barlett, Xiao Guang Yang, Valentina Mejia, Min Zhu, Yijung Chen, A distributed randle circuit model for battery abuse simulations using LS-DYNA, presented at the 14th International LS-DYNA Users Conference, 2016.

[2] Wei-Jen Lai, Mohammed Yusuf Ali, Jwo Pan, Mechanical behavior of representative volume elements of lithium-ion battery modules under various loading conditions, J. Power Sources 248 (2014) 789-808.

[3] Chao Zhang, Shriram Santhanagopalan, Michael A. Sprague, Ahmad A. Pesaran, Coupled mechanical-electrical-thermal modeling for short-circuit prediction in a lithium-ion cell under mechanical abuse, J. Power Sources 290 (2015) 102-113.

[4] Chao Zhang, Shriram Santhanagopalan, Michael A. Sprague, Ahmad A. Pesaran, A representative-sandwich model for simultaneously coupled mechanical-electrical-thermal simulation of a lithium-ion cell under quasi-static indentation tests, J. Power Sources 298 (2015) 309-321.

[5] J.O. Hallquist, LS-DYNA Keyword User's Manual, Vol. I, II & III, May 2014, Livermore Software Technology Corporation (LSTC), 2015.

[6] J.O. Hallquist, LS-DYNA Theory Manual, March 2006, Livermore Software Technology Corporation (LSTC), 2012.

[7] Elham Sahraei, Rich Hill, Tomasz Wierzbicki, Calibration and finite element simulation of pouch lithium-ion batteries for mechanical integrity, J. Power Sources 201 (2012) 307-321.

[8] Elham Sahraei, Joseph Meier, Tomasz Wierzbicki, Characterizing and modeling mechanical properties and onset of short circuit for three types of lithium-ion pouch cells, J. Power Sources 247 (2014) 503-516.

[9] Tomasz Wierzbicki, Elham Sahraei, Homogenized mechanical properties for the jelly roll of cylindrical Lithium_ion cells, J. Power Sources 241 (2013) 467-476.

[10] Lars Greve, Clemens Fehrenbach, Mechanical testing and macro-mechanical finite element simulation of the deformation, fracture, and short-circuit initiation of cylindrical Lithium ion battery cells, J. Power Sources 214 (2012) 377-385.