Numerical Simulations in Mechanical Engineering

Topic 3: Fracture and failure of battery shell

By

Chunhao Yuan

Aditya Sonwane

Department of Mechanical Engineering and Engineering Sciences

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Abstract

Safety is the key and fundamental performance of the battery. Due to inevitable abusive scenarios such as overcharging, penetration, overheating and high-speed collision, various types of failure behaviors of battery component materials, thermal runaway or even fire/explosion may occur to power lithium-ion batteries (LIBs), posing great threatens to the society.

Mechanical integrity of LIBs now becomes a determinant factor for electric vehicle safety, and it attracts global attentions from both industry and academy, however, limited progress has been achieved due to its complexity nature. Generally, battery shells serve as the protective layer for LIBs to withstand external mechanical loading and sustain the integrity of electrochemical functioning environment. Understanding the mechanical behaviors of LIB shell material especially dynamic behaviors shall play a paramount role in unraveling the mechanical integrity of the LIB cell and pack.

In this project it is expected to use numerical simulation tools to study the fracture and failure of the battery shell. The Shell is of 18650 LIB, made up of stainless steel. The mechanical responses of battery for indentation and axial loading are analyzed and discussed. The established model can well predict the mechanical behavior of battery, thus directing the safety design and operation of battery.

Introduction

Lithium ion batteries have a wide range of applications from electronics to electric vehicles. LIBs used in electric vehicles need to be designed for safety of the vehicle. It is needed that the material of the battery is strong enough to sustain in an event of crash. Due to the same reason the battery is made to go under various loading tests to have a better design for the vehicles. Since the anode and cathode are delicate materials and are surrounded and protected from environmental harms by the steel casing. It is made sure the shell is up to expectations for any loading like indentation, penetration, crushing, tension, etc. The project report here will provide simulation and experimental comparison and validation of model is provided. Finite Element Analysis simulations of indentation and axial loading of the battery shell along with the procedure to model the shell and all the failure and fracture model is carried out.

Finite Element Modelling procedure

The battery used in the experiment is 18650. Taking the dimensions of the same battery fro the simulations, the diameter of the battery shell is 18 mm and since for testing the shell was cut from ends its length is reduced to 46 mm. following figures show the dimensions and assembly of both loading cases i.e. axial compression and radial indentation.

1. Axial compression loading.
2. Radial indentation loading.

1. Axial Compression loading

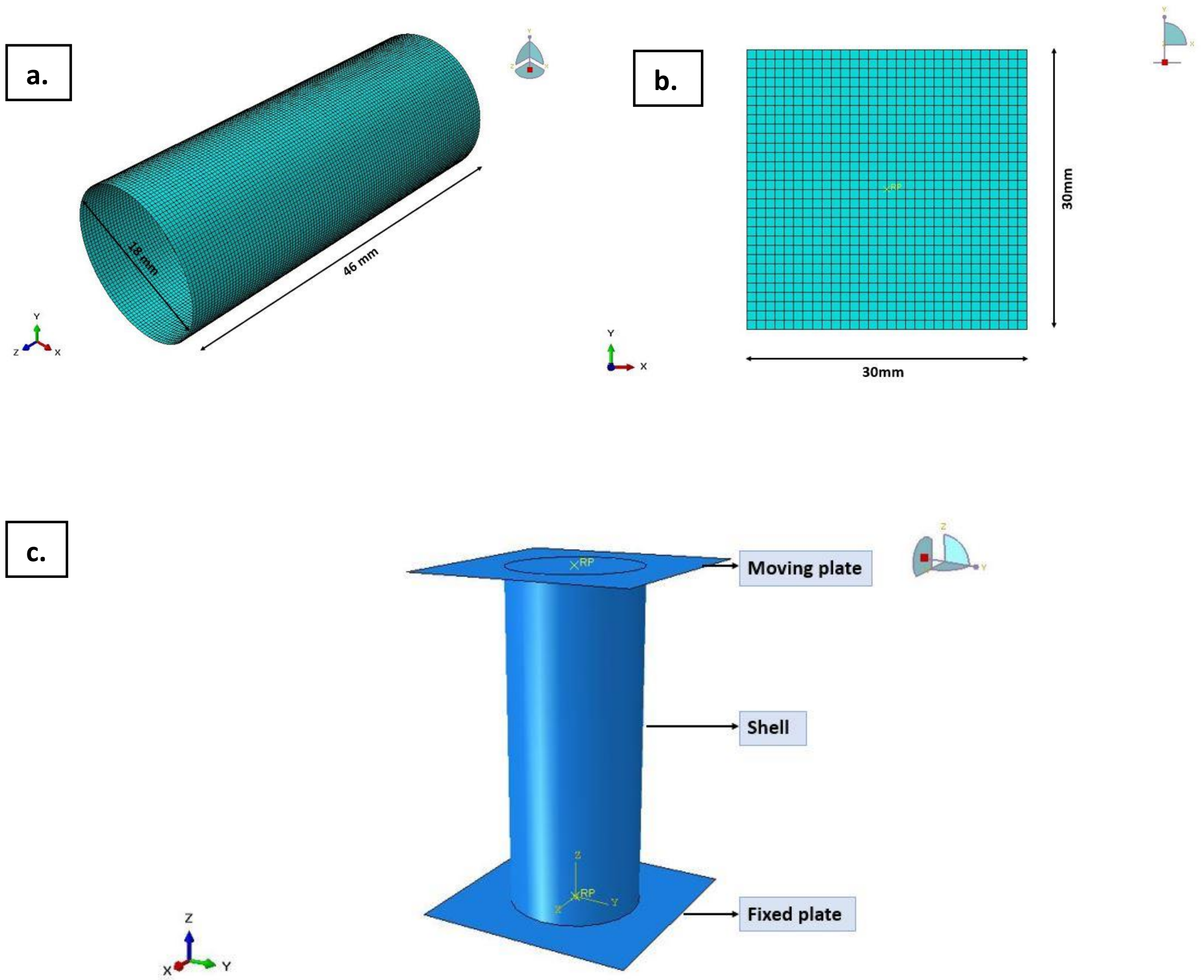

Fig.1. Axial Compression loading, (a) Battery shell, (b) Rigid plates, (c) Assembly.

2. Radial indentation loading.

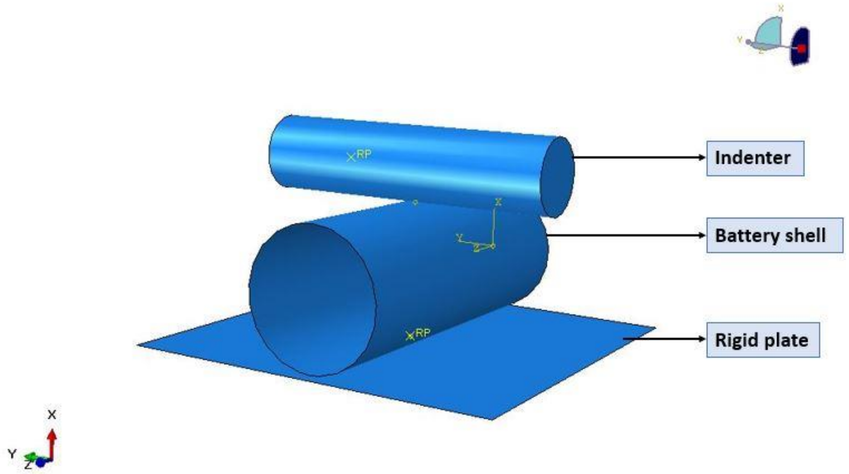

Fig.2. Radial indentation loading, (a) Indenter, (b) Battery shell, (c) Rigid base plate, (d) Assembly

Element meshing

Each part of the assembly of the axial loading and the radial loading are meshed to get good simulation results as per the experiment. Details on each assembly and its components is given below.

Assembly	Component	Element type	Element size	Element number
Axial loading	Battery shell	Shell	0.4 mm	16215
	Rigid plate	Shell	1 mm	900
Radial indentation	Battery shell	Shell	0.4 mm	16215
	Indenter	Solid	0.5 mm	5919
	Rigid plate	Shell	1 mm	2500

All the shells are meshed using S4R quadrant and the solid indenter is meshed using quadrant dominated mesh.

Materials of the components

Since the rigid plates have no material properties, there are just two components that need the material properties i.e. the battery shell and the indenter. Details of the materials used for the components are given in the table

Component	Density	Elastic modulus	Poison's ratio	Plastic model
Battery shell	$7.8*10^3$ kg/m^3	211 GPa	0.3	$\sigma = (740 + 249\varepsilon_p^{0.46})$
Indenter	$7.8*10^3$ kg/m^3	211 GPa	0.3	$\sigma = (740 + 249\varepsilon_p^{0.46})$

In addition to the plastic model to the battery shell, Johnson-Cook damage is used to get the failure and fracture in the simulation the Johnson-Cook model equation from the reference is given as:

$\varepsilon_f = 0.001281 + 658.6 * e^{-32.59\eta}$

Section properties

For the section properties the shell used for the battery has a thickness of 0.11 mm. section type used is Shell homogeneous. Similarly for the indenter it is Solid homogeneous.

Contact conditions

Both the axial loading and the radial indentation loading assembly use general contact algorithm since the whole model is an Explicit model.

Boundary conditions

For Axial loading:

The bottom plate is made fixed and the other plate on the top of the assembly has a displacement boundary condition. As per the modelling the displacement is given is of 45 mm in Z direction to obtain crushing or compression of the shell. The rotational displacement of the shell is also restrained to obtain ideal crushing scenario.

For Radial indentation loading:

In this case the bottom plate acts as the rigid support and is made fix as the platform in experiment. The indenter has a displacement boundary condition, with a displacement of 15 mm in X direction as the model has the assembly as such which results in the indentation similar to the experiment.

Simulation results

The simulations of the axial loading and the radial indentation loading are compared with the experimental results from the reference paper by the Force v/s Displacement curve. Giving the validation of the results obtained from the simulation and the experiment as well. The curves follow similar trend and match well but with a ringing in the simulations dur to ideally controlled simulation environment, but the failure and fracture of both cases for simulation is nearly same as that of experiment.

Following figures show the comparison of the results and the simulation on the battery shell:

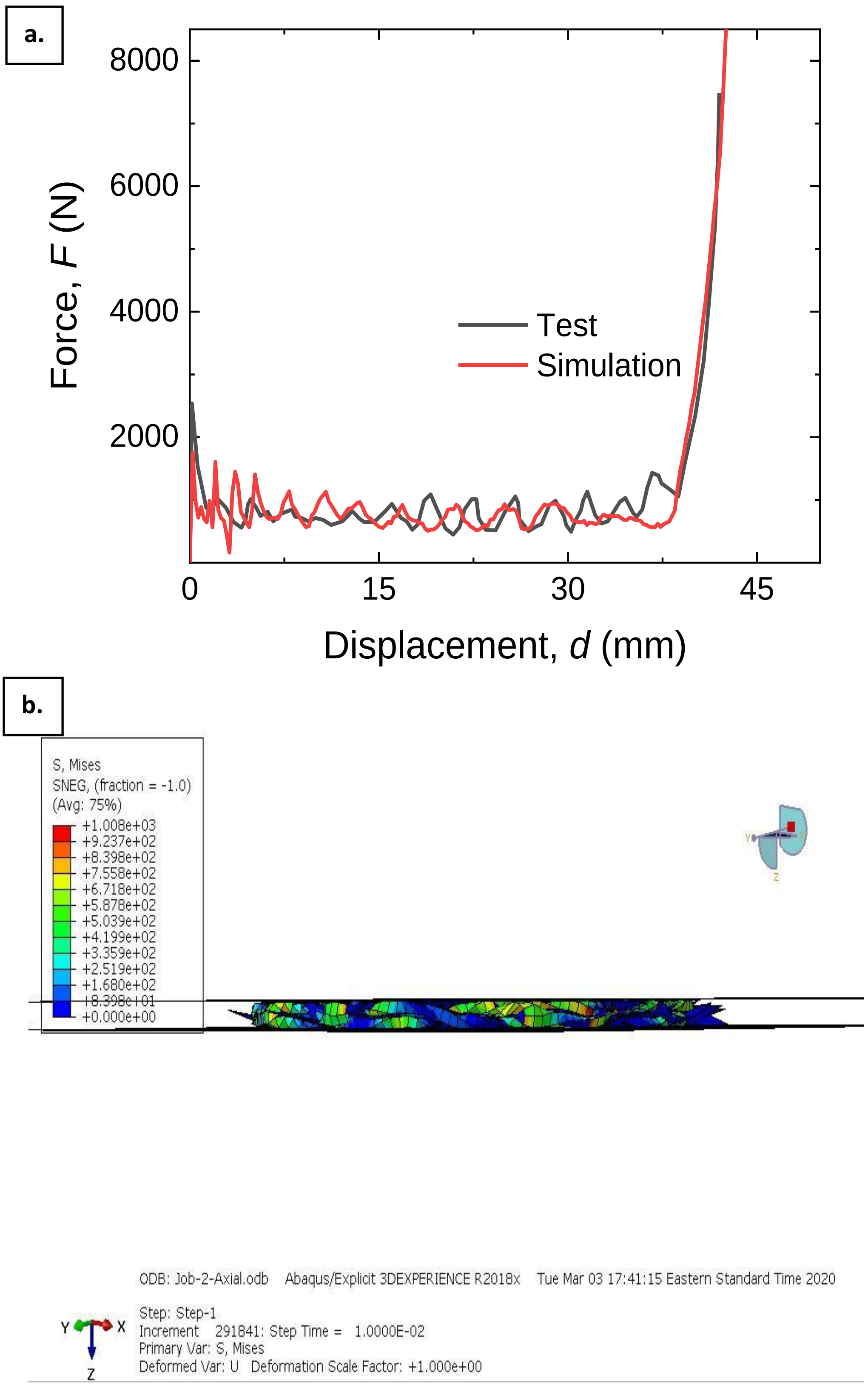

Fig.3. (a) Simulation and experiment result comparison with (b) Von Mises contour for complete axially crushed battery shell.

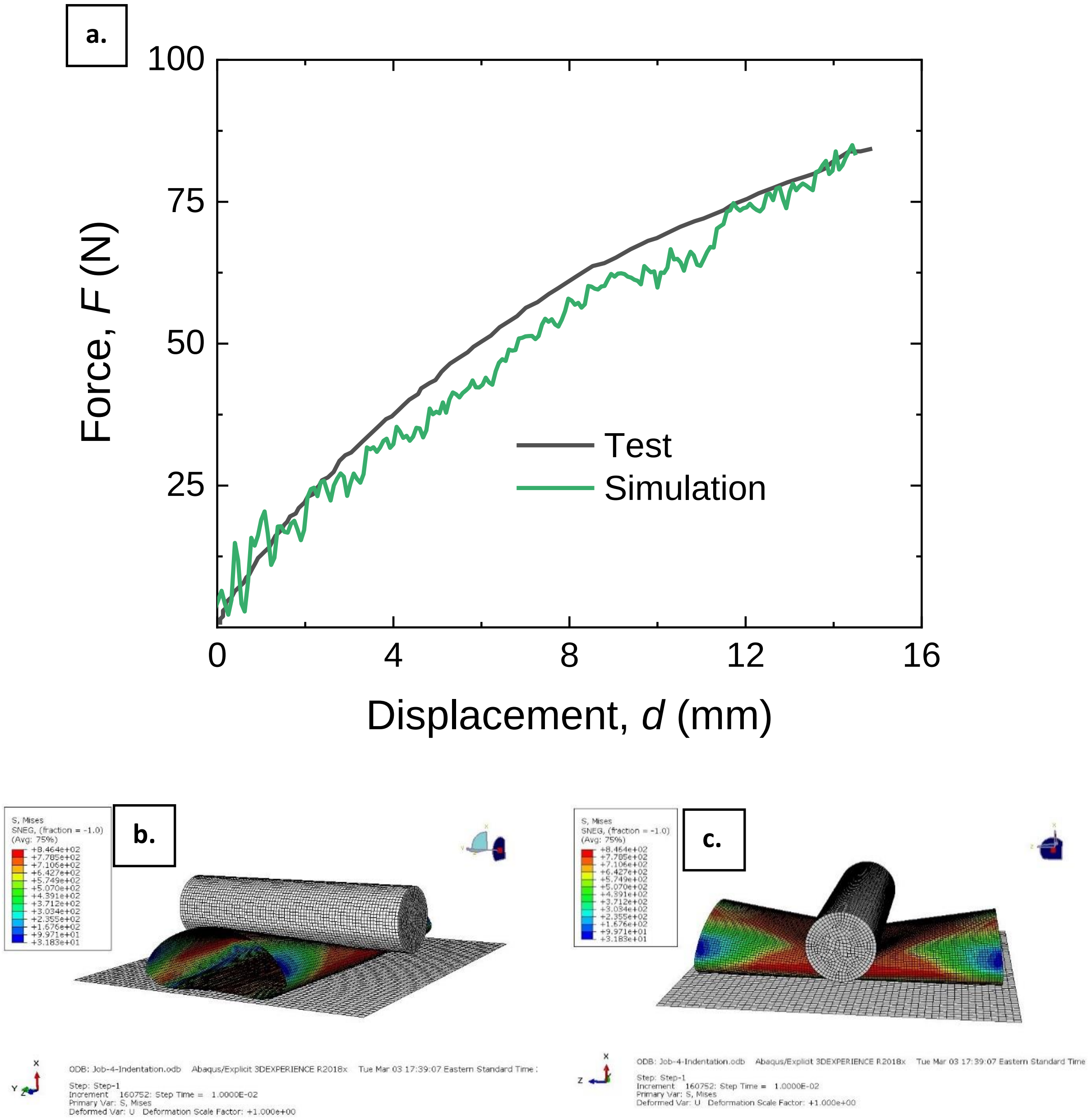

Fig.4. (a) Simulation and experimental result comparison with (b)& (c) Von Mises contour for complete radially indented battery shell.

Discussion

Axial loading case:

Taking a look at the simulation and experimental comparison of the force vs displacement curve it can be seen that the ringing starts in the simulation even with low displacement and continues until the failure of the shell and the force increases as the displacement goes on increasing until the shell is crushed and failed completely. The results from the simulation nearly match the experimental results. Since the environmental factors are not taken in to consideration the simulation results may vary. But looking at the comparing plot it shows the failure for the simulation is later than that of the experimental plot. The slope at the end of plots is steep and match very well which gives a validating proof of the simulation and the experimental results.

Figure below shows the various crushing stages in the axial loading for different displacements as the simulation proceeds to failure.

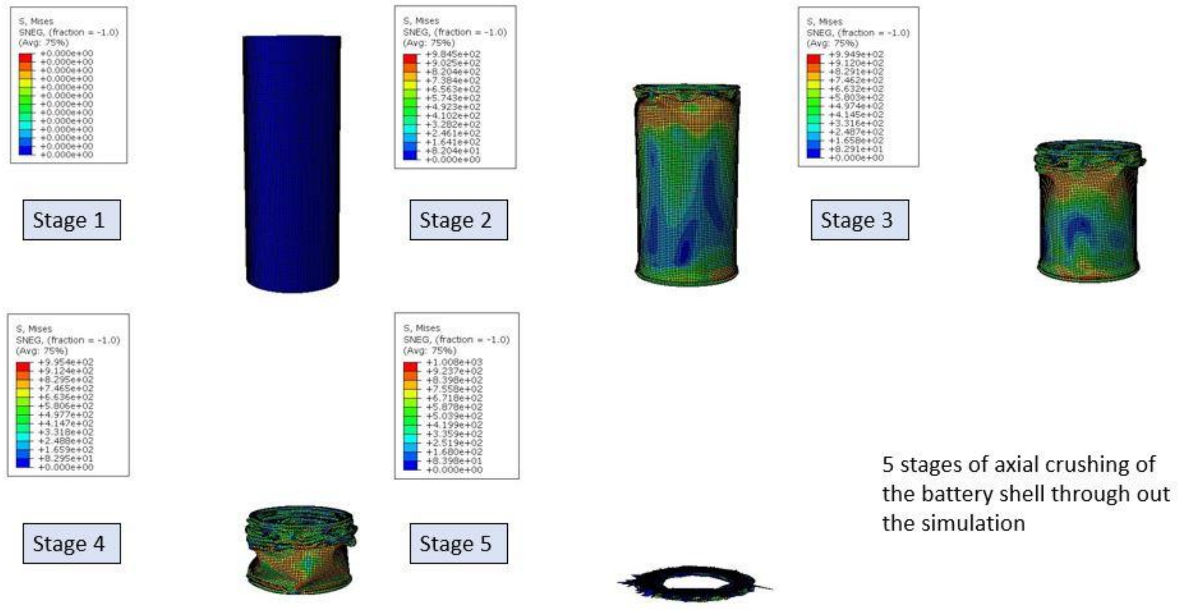

Fig.5. Stages of crushing the battery shell in axial loading.

Radial indentation loading:

From the comparison plots of the simulation and experimental results for Force vs displacement, it is observed that the plots for both follow same trend and nature until fracture but as like previous case there is ringing in the simulation data. This ringing is the result of the ends of the shell which are in contact with the indenter which get hard and need more force to deform. As soon as this stage is over the force drops and it deforms the remaining part of the shell. The cycle of increasing and decreasing the force i.e. the ringing observed is till the failure and fracture of the shell. But at the ends of the simulation the frequency is reduced as much of the shell is already deformed and crushed. The failure of the experimental plot occurs little bit later than the simulation plot.

Following figure shows various crushing stages of the radial indentation loading at different instance of the displacement.

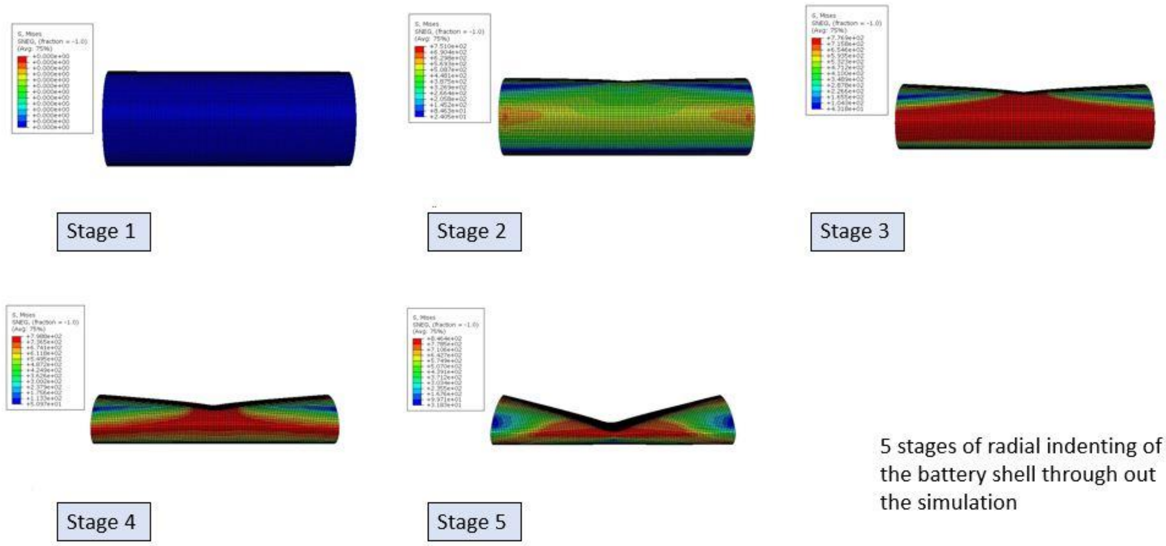

Fig.6. Stages of crushing the battery shell in radial indentation loading.

References

[1] Wang, Lubing, et al. "Unlocking the significant role of shell material for lithium-ion battery safety." *Materials & Design* 160 (2018): 601-610.