

Structural Design and Assessment of EV Battery Module for Shock Resistance

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Abstract: With ownership of electric vehicles (EV) increasing, greater attention is being paid to their safety. As the energy storage component in pure electric vehicles, the safety of the battery is particularly important. Cylindrical batteries are still commonly used in electric vehicles, especially the 18650-battery type. Indentation, tension and compression tests have been carried out on this battery by many researchers. However, to date, shock testing of battery packs has received less analytical focus. In this paper, a homogeneous model of a battery pack consisting of nine aligned cells is developed, whereby the shock signals specified by the UN38.3 standard are applied in three directions in space. Simulations are carried out in ABAQUS after setting material parameters and constraints to obtain stress, strain and deformation results, as well as variations of impact acceleration. The simulated stress results were compared with the mechanical properties of the material according to their maximum stress criteria, whereby it is found that the battery pack would not fail under any of the three operating conditions. Through the fast Fourier transform, it is ascertained that the shock signal, after propagating through the battery pack, has an acceleration maximum in the frequency domain only at 0Hz. The model employed in this paper effectively simplifies the calculation process and ensures the accuracy of the calculation.

Keywords: EV; 18650 battery modules; shock test; ABAQUS; UN38.3

1. INTRODUCTION

Since their inception, automobiles have undergone continuous innovation to meet societal needs. With rising concerns over the environmental impact of internal combustion engines, global efforts are increasingly directed toward new energy vehicles (NEVs), particularly pure electric vehicles (EVs). Although petrol- and diesel-powered cars remain dominant, their widespread use exacerbates energy demand and environmental pollution, highlighting the strategic importance of EV development for sustainable economic and environmental goals.

Electrification has become a key trajectory in the automotive industry, reinforced by national policies. Urban EVs, including the Tesla Model 3, Toyota Prius, and BYD electric buses, have led early adoption, while growing consumer confidence in safety and reliability has expanded the market to include SUVs and commercial engineering vehicles, such as the NIO ES8 and BYD Tang. This trend underscores the need for robust safety standards across diverse operational conditions.

Battery packs, as the core energy storage units, are frequently implicated in EV fire incidents. Failures arise from spontaneous combustion, charging faults, or vehicle collisions, with a high proportion caused by impact events. Collisions can damage the pack structure, disrupt internal contacts, and induce short circuits, potentially triggering fire hazards. Mounted under the vehicle chassis, battery packs are particularly vulnerable to localised impacts, road-induced shocks, and random vibrations, which may result in structural deformation, fracture, electrolyte leakage, and reduced component lifespan.

Given these high-risk scenarios, rigorous impact analysis is essential. Simulation-based verification enables precise prediction of battery pack dynamic responses under crash and

road-induced loads, guiding structural optimization to enhance energy absorption, impact resistance, and internal component protection. Such simulations provide critical insight into deformation mechanisms and potential failure modes, supporting design improvements that mitigate fire risk and extend operational reliability.

As EV adoption accelerates in increasingly complex environments, integrating impact-resilient design with comprehensive simulation validation is imperative. This approach not only ensures battery safety and structural integrity but also underpins public confidence and facilitates the sustainable proliferation of EVs. Ultimately, simulation-driven assessment represents a cornerstone of EV battery development, providing a systematic framework to anticipate hazards, optimize design, and secure both performance and safety under real-world operating conditions.

2. Model Building and Mesh Generation

2.1 Model Building and Parameter Settings

As mentioned, there are two main arrangements of single cells in battery packs used in electric vehicles with cylindrical cells as a single cell: cubic and hexagonal. The hexagonal arrangement takes up less space, but is more difficult to fix. The cubic arrangement exhibits better thermal performance. This paper presents a simulation of a cubic arrangement of an 18650-battery pack under impact.

Usually a battery pack consists of more than 7000 individual cells, and although a finite element analysis of the whole pack may produce more accurate results, it is too computationally intensive, especially when a mesh needs to be generated for each cell in the simulation software. Therefore, taking reference from many validated research papers, this thesis selects nine adjacent single 18650 cells from a whole pack to form a battery pack. Also, many researchers have demonstrated that homogenising the model not only reduces

the computational effort but also ensures high simulation accuracy. Therefore, each 18650 cell is also homogenised in this paper. In order to impose constraints later on, the battery is also modelled with concordant housing, which is made of an aluminium alloy, type 3003. As the internal structure of the battery is not provided for, geometric modelling is undertaken directly in ABAQUS, as shown in Figure 1.

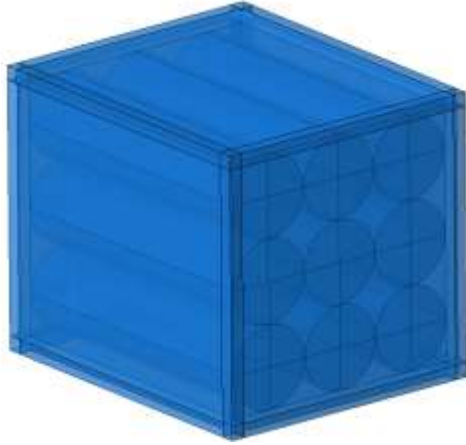


Figure 1. Battery model in ABAQUS.

For the homogeneous model used, it is crucial to determine the material parameters. The battery pack model is divided into 2 main parts: the battery and the housing. In this paper, the parameters of the homogenised model are determined by referring to the relevant literature in Table 1; for the parameters of the aluminium alloy housing, please consult Table 2.

Table 1. Parameters of homogenous 18650 battery [1]

Terms		Values
Diameter (mm)		18
Height (mm)		65
Weight (g)		45
Equivalent density (g/mm ³)		0.002721
Reference yield stress (MPa)		5
Hardening exponent		5.9
Elastic modulus (MPa)	E_1	260
	E_2	260
	E_3	1200
	G_{12}	118
	G_{13}	500
	G_{23}	500
Poisson's ratio	ν_{12}	0.1
	ν_{13}	0.08
	ν_{23}	0.08

Table 2. Parameters of aluminium alloy shell

Terms	Values
Size (mm*mm*mm)	60*60*71
Thickness (mm)	3
Density (g/mm ³)	0.0027
Yield strength (MPa)	125
Tensile strength (MPa)	130
Shear strength (MPa)	83
Elastic modulus (GPa)	70
Poisson's ratio	0.33

Having defined the material properties, the next step is to define the contact relationships and constrained relationship between the elements in ABAQUS, as illustrated in Figure 9. The proposed cubic arrangement comprises cells with generic contact between each other, as well as between the upper and lower circular surfaces of the cell and the case. The front and rear faces of the battery are bound to the inner surface of the case. At the same time, the shell material of the 18650 type lithium-ion battery is predominantly steel or aluminium shell [2], as well as the shell used in this paper being an aluminium alloy, so the friction coefficient at contact is taken as 0.15, which is the common metal-to-metal friction coefficient.

This paper explores the effects of shocks on battery packs. Due to the constraints of obtaining an actual shock signal during the driving of an electric vehicle, the shock signal utilised for the purposes of this the shock test is UN38.3. The shock signal is a half-sine wave with a maximum acceleration of 150gn and a pulse duration of 6 milliseconds, as illustrated in Figure 2. The acceleration of gravity is represented by gn, which here is equal to 9.8m/s².

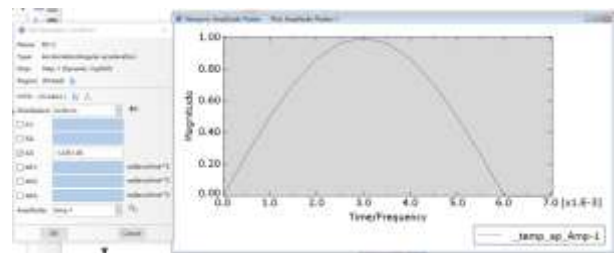


Figure 2. Shock loading signal.

In order to comprehensively explore the impact of impact load, in this paper, the half-sinusoidal shock wave specified in UN38.3 is applied to the battery pack from the directions of Z in space, respectively. The shock applied in the Z direction, that is, parallel to the axis of the cylindrical battery.

2.2 Mesh Generation

In this session, mesh generation is performed separately for the single cell and the housing. Hexahedral elements are the best choice when performing mesh generation operations on 3D structures, as tetrahedral elements are relatively less accurate in simulation contexts. Furthermore, when cell volumes remain the same, the number of elements divided by

a hexahedral mesh is less than the number of cells divided by a tetrahedral mesh for the same object under study, resulting in less simulation computation time. Last but not least, the hexahedral mesh elements are closer to the physical field being simulated. As the battery housing is inherently hexahedral, the mesh shape is not easily deformed when using hexahedral cells to generate the mesh.

As the homogenised model of the 18650 Li-ion battery is cylindrical, when the hexahedral mesh is automatically generated, the structure is in a swept state and some of the hexahedral cells are deformed, thus the shape is close to a tetrahedral, rendering the meshing less accurate. Accordingly, the division of the cell structure was undertaken with two vertical lines of symmetry of circular cross-section to structure the cell model. The mesh shape has been significantly improved following the division. Not only that, but result implies that the number of cells has also been increased after the re-division, indicating that simulation accuracy will be improved.

Finally, the cells and the housing were assembled together after the mesh was generated, as shown in Figure 3. In addition to this, the total number of nodes, the total number of cells and the cell type of the battery pack model are also conveyed in Figure 4.

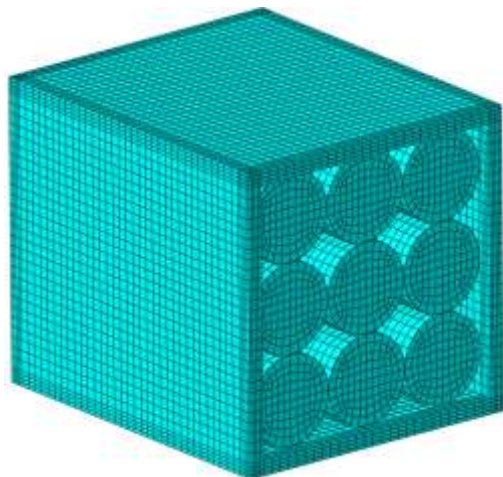


Figure 3. Battery module mesh.

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Total number of nodes: 69214
Total number of elements: 57056
30952 linear hexahedral elements of type C3D8R
26104 linear hexahedral elements of type C3D8I
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Figure 4. The information of battery module after mesh generation.

3.Results and Discussion

Once the results of the stress, strain and deformation data mentioned above have been obtained, all that remains is to determine whether the battery pack will fail after it has been subjected to an impact. It is therefore essential to choose the appropriate failure criterion. However, different parts of the battery pack will use different materials and have different shape characteristics, just as materials are divided into brittle and plastic materials. Resultantly, it is quite difficult to predict insofar that there is no one universally applicable method. The most common method employed to predict product failure by comparing the tested or simulated stress state with the yield stress or ultimate strength of the material used. The so-called stress state is usually articulated in terms of the principal stresses in the three directions in space of the object under test, so that most failure criteria are considered a function of

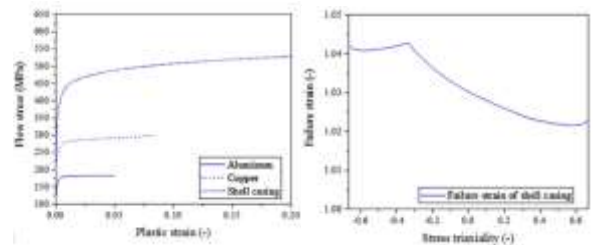
the three principal stresses and the strength of the material, represented by the equation below.

$$F(\sigma_1, \sigma_2, \sigma_3) = \sigma_y, \sigma_u$$

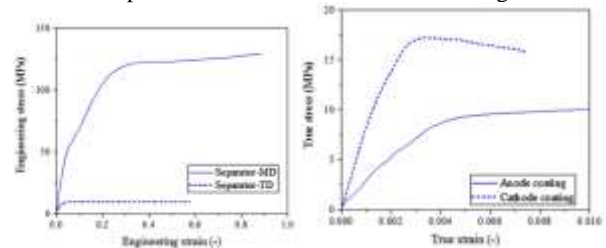
Where σ_1 , σ_2 and σ_3 are the principal stresses, σ_y is yield strength, σ_u is ultimate strength.

The most commonly employed and simplest stress failure criterion is the maximum stress criterion, which means that when a product is tested in a particular way, the absolute maximum value of the principal stresses generated reaches the yield or ultimate strength of the material. This criterion is a type of non-interactive failure criterion.

For the purposes of this paper, the maximum stress criterion is used to determine whether a battery pack will fail after being subjected to an impact load as specified in UN38.3. The work to be done, therefore, divided into two main parts, one of which is to find the principal stresses in the battery pack after impact and the other is to determine the material parameters of the battery pack. In particular, it is important to note that this paper focuses on exploring the impact of the shock on the battery, so it is still chosen to remove the case representation when determining failure in this section. As mentioned above, the 18650 cylindrical cell includes the separator, electrodes and electrolyte, which are manufactured using different materials and even in different physical states. The cell model in this paper has been homogenised, so it is difficult to determine the exact material properties of this homogenised model (such as yield strength and ultimate strength). Therefore, by referring to Zhu et al. (2016) the mechanical property curves of the main internal components of the cell, such as the separator, housing and electrodes, were obtained as shown in Figure 5 (a), (b), (c) and (d).



(a) Hardening curve of three components (b) fracture locus of the shell casing



(c) engineering stress-strain curve of the separator (d) tensile true stress-strain curve

Figure 5. Mechanical properties of the components of the 18650 battery.

While the axes in the graphs are all different, they can all be interpreted as indicators of the stress at which the component fails or yields. It can be seen that the shell is the strongest, but less ductile. The anode shell, on the other hand, has the lowest strength even though it is more ductile. Therefore, in order to ensure the safety of the battery, the lowest value of strength,

10 MPa, is taken as the mechanical characteristic of this homogenised model.

Figure 6 reveals how the principal stresses derived from the three respective directions in space behave on the battery pack when it is subjected to an impact from the Z-direction. In ABAQUS, S11 represents the principal stress in the X-axis direction, with positive values indicating the tensile state and negative values indicating the compressive state. Similarly, S22 represents the principal stress in the Y-axis direction, and S33 represents the principal stress in the Z-axis direction. Also, the three directions of principal stress are included in the ABAQUS representation with regards to direction.

In contrast, the von Mises stresses alluded to in the previous section are all positive and do not imply the direction of the stresses. The relationship between principal stresses and von Mises stresses is demonstrated by the following equation.

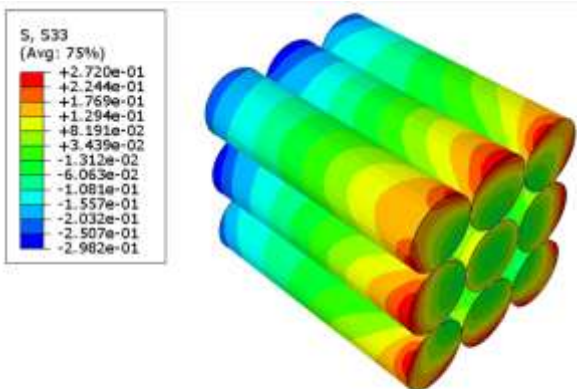
$$\sigma = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

Where σ is von Mises stress, σ_1 is S11, σ_2 is S22, and σ_3 is S33.

As can be seen in Figure 6(a), the absolute value of the principal stress in the z-axis direction is closest to the von Mises stress described earlier for this impact condition. The end-face of the cell at the impacted surface exhibits a tensile state, while its opposing face manifests a compressive state. The absolute value of the stress in the middle of the cell remains the smallest. For the principal stress states in the X- and Y-axis directions, the two cases are similar, exhibiting similar stress values, but both are smaller than the principal stresses in the Z-axis direction; furthermore, the distribution of their absolute maximum values in space is also consistent with the corresponding principal stress directions. The absolute maximum value of the principal stress appears to be 0.2982 MPa in the Z-axis. That is to say, that the following condition is satisfied.

$$0.2982/10=0.02982<1$$

When the battery pack is subjected to an impact from the Z-direction, the pack will not fail according to the maximum stress criterion; moreover, the difference from the critical stress of 10 MPa is substantial, meaning that it can withstand larger shocks.



(a) S33 when applying Z-direction shock loading

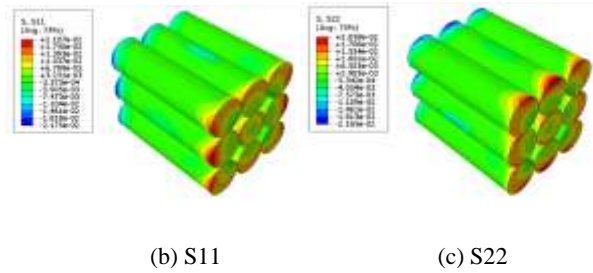


Figure 22. Principal stresses when applying Z-direction shock.

4. Conclusion

After a concise introduction to the development of electric vehicles and the importance of battery pack safety, this paper conducts a shock simulation analysis via ABAQUS of a battery pack consisting of the commonly-used 18650 type battery for pure electric vehicles. Considering that the actual battery pack at the point of use of an electric vehicle includes more than 7000 individual cylindrical batteries, the battery pack employed in this simulation consists of 9 individual batteries in order to reduce the necessary amount of computational resource and to ensure the accuracy of the simulation to a certain extent, as well as to obtain a relatively accurate impact response profile of the battery pack.

In addition, the internal structure of each 18650 battery is replaced by a homogenised model, reducing the number of nodes used in the simulation and further simplifying the calculation of the model. Many studies have demonstrated that the simulation results obtained using the homogenised model are in good agreement with the experimental results; therefore, homogenised models are now often used in industrial or laboratory simulations to reduce the computational effort and improve the efficiency of the simulation, whilst maintaining the accuracy of the simulation. The shock signal used in this simulation is a half-sine wave shock signal with a maximum acceleration of 150gn and a duration of 6 milliseconds as specified in the UN38.3 standard. After setting the material parameters, battery constraints and boundary conditions, the simulations were carried out in ABAQUS.

The results obtained from the simulation include stresses, strains, deformations and the variation curves in the time domain of the shock acceleration after passing through each cell in the battery pack. This paper focuses on the analysis of the simulated stress results. When the battery pack simulation results include the housing, the maximum stress is 3.731 MPa when the shock is applied from the Z-axis direction, and 2.7 MPa when the shock is applied from the other two directions. On the other hand, for simulation results which do not include the housing, the maximum stress drops significantly, especially when the shock is applied from the Z-direction, with a maximum stress of 0.2843 MPa. This phenomenon indicates that the aluminium alloy housing suggested herein can absorb most of the impact energy when the battery pack is subjected to an impact, effectively protecting the internal battery. Meanwhile, the maximum stresses often occur at the two end-faces of the battery, so it is necessary to further secure the battery by utilising stronger materials at this location or by providing special protection at the point on the housing which comes into contact with it. The trend of strain and deformation is found to be in good agreement with the stress.

6.ACKNOWLEDGMENTS

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