Study on the Battery Safety in Frontal Collision of Electric Vehicle

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Abstract. With the rapid development of electric vehicle industry, more and more attention has been paid to the safety of the automotive battery. The safety of battery in electric vehicle’s frontal collision is the focus of this paper. In the process of simulated collision, the research object is simplified into a battery box. The mechanical properties of the battery monomers were investigated to summarize the mechanical properties of the internal failure of the monomers. Constructing the finite element model of the research object, we focus on the analysis of collision simulation results and propose the improvement measures. According to the test requirements in C-NCAP, the crash simulation of battery box is carried out by using the finite element software called LS-DYNA, which is used in automobile collision to analyze the deformation, stress of the battery box and the most dangerous battery monomer during the frontal collision. The simulation results show that the deformation of the case is obvious, and the protection of the battery is lost in the 50km/h frontal collision condition. By adding EVA foam, the maximum deformation of the battery monomer is reduced by 8.2%. By improving the material of battery case, the maximum deformation is reduced by 12.65%.

1. Introduction
In recent years, new energy vehicles have developed rapidly due to the intensification of energy shortage and environmental pollution. Electric vehicles have gradually become the mainstream of contemporary automobile with their advantages of simple structure, low energy loss of mechanical parts and low noise. However, the safety of electric vehicle needs to be improved urgently, especially the collision safety. According to incomplete statistics, there were as many as 124 cases which reported that electric vehicles caught fire in China in 2020, many of which were caused by battery fire after collision. It is urgent to improve the battery safety during electric vehicle collision. Scholars at home and abroad have carried out a lot of research in the collision safety test and simulation of electric vehicles. A Simeone et al. conducted bench test on the impact damage of lithium-ion battery and evaluated the impact damage of battery in terms of physical performance and electrical performance [1]. F C Lan et al. proposed the expansion response analysis method for the battery pack case and internal structure, established the finite element model of the electric vehicle, and evaluated the safety of the battery by analyzing the deformation in side impact simulation [2]. J Wang et al. analyzed battery safety in terms of force transfer
in frontal collision and case structure deformation by building a vehicle finite element model and proposed corresponding optimization schemes [3]. The finite element models of battery monomer and battery case are built in this paper, and the grid is divided. The 50km/h frontal collision simulation is completed with LS-DYNA. The stress and deformation curves of monomer and battery case in the simulation results are analyzed to describe the battery safety performance of electric vehicle in specific working conditions. Based on this, the structure of battery protection package is optimized to improve the collision safety of electric vehicles.

2. Collision safety regulations

In order to ensure the collision safety, all countries in the world have formulated corresponding mandatory regulations. The existing collision test systems mainly include NCAP (New Car Assessment Program) and IIHS (Insurance Institute for Highway Safety). Based on NCAP, Europe developed the Euro-NCAP standard, and Japan developed the J-NCAP standard. China also formally proposed the C-NCAP standard in 2006, in which the regulations on electrical safety of blade electric vehicle/hybrid electric vehicle are as follows [4]:

(1) Voltage Security: after the crash test, the voltage shall not exceed 30V AC or 60V DC.
(2) Power Safety: after the collision, the total electric energy and capacitor energy \( TE_{\text{1}} + TE_{\text{2}} \) shall not exceed 0.2J.
(3) After the collision, there shall be no electrolyte in the crew compartment, and a maximum of 5L electrolyte shall be allowed to overflow from the REESS.
(4) During the collision, the REESS in the crew compartment remains immobile. Components of the battery box shall not enter the inside of the box, and the battery box shall not invade the crew compartment.
(5) After the collision, the battery box shall not catch fire or explode.

3. Selection and modeling of power battery pack

3.1. Selection and structure of battery

As one of the main components of electric vehicles, battery pack is the power source of electric vehicles. At present, on-board batteries are used as the power source by most blade electric vehicles, and lithium-ion batteries have become the mainstream power source of electric vehicles with the advantages of high working voltage, high proportional energy, and long service life [5], such as lithium cobalt oxide battery used by Tesla and lithium manganate battery used by Toyota Prius.

The 98B0F5 lithium-ion battery is selected in this project. The parameters are shown in Table 1. The power system consists of 12 monomers in series to form a battery module, and the two modules are connected in parallel to form a power battery pack. Different finite element models of the battery enjoy different advantages. Considering that in the existing research, the refined model is better than the homogeneous model to reflect the deformation and failure of the battery under load, the project adopts the refined modeling method to conduct mechanical test simulation of 98B0F5 terpolymer lithium battery. The model is divided into four layers: positive electrode (including current collector and active substance coating), negative electrode (including current collector and graphite coating), diaphragm (polyolefin film and ceramic coating) and aluminum-plastic film (nylon layer, aluminum foil layer and heat-sealing layer).

| Name               | Specification            | Name               | Specification         |
|--------------------|--------------------------|--------------------|-----------------------|
| Battery model      | 98D0F5-0601              | Size               | 112mm×160mm×9.8mm     |
| Anode material     | Lithium nickel chromium-aluminate | Monomer mass   | 300g                  |
| Nominal capacity   | 17.8C                | Charging temperature range | 10-45°C               |
3.2. Three-dimensional model of battery pack

As is shown in Figure 1, the battery box is composed of case, division board and battery module. The external size is 227mm×199.6mm×162mm. The thickness is 1mm. The monomer mass is 300g and the dimension is 112mm×160mm×9.8mm. The module consisting of 24 monomers in series and parallel is fixed in the case. The overall mass of the battery box is 16.2kg.

Figure 1. The structure diagram of battery box

More attention is paid to the deformation of battery case in collision and its impact on battery safety. To simplify the calculation, the battery case and monomer model are simplified. Additionally, the circuit design, heat dissipation structure and external connection of the battery case are not considered. The battery box is simulated as a whole, and the middle partition plate is used to restrict the battery module from moving arbitrarily in the left and right directions during the normal running of the automobile.

3.3. Finite element model of battery pack

3.3.1. Material model. According to the collision test standard, the rigid wall is defined as a rigid body with no deformation and no displacement. The material model is selected in LS-DYNA, and the compressible foam is used for the battery monomer. The material parameter settings of case and battery monomer are shown in Table 2. According to the principle of consistent quality, the monomer density can be calculated: \( \rho = 1780 \text{kg/m}^3 \).

Table 2. Material parameters

| Name                          | Material   | Density (\(\text{kg/m}^3\)) | Poisson's ratio | Elastic modulus (GPa) | Yield strength (MPa) |
|-------------------------------|------------|------------------------------|-----------------|-----------------------|---------------------|
| Case (including division board)| Steel      | 7580                         | 0.3             | 206                   | 0.345               |
| Battery                       |            | 1780                         | 0.01            | 0.5                   | -                   |

3.3.2. Meshing. Considering that the deformation of the battery case in the collision simulation is nonlinear with large displacement and the model of the power battery box is thin-walled structure, it is simplified into shell after extracting the middle surface. SHELL163 unit is selected for grid division of case, and SOLID164 unit is selected for battery monomer. The rigid wall is not taken as the research object, and SHELL163 is selected. ALE method is adopted for unit algorithm. Overall grid size is limited to 5mm. Grid quality parameters and related standards are shown in Table 3.
### Table 3. Mesh quality attributes

| Name                      | Standard | Actual value |
|---------------------------|----------|--------------|
| Warpage factor            | 0        | 1.4E-10      |
| Skewness                  | 0        | 4.7E-3       |
| Maximum internal angle    | $<140^\circ$ | 111.57$^\circ$ |
| of quadrilateral element  |          |              |
| Element aspect ratio      | $\leq 4$ | 3.297        |
| Jacobi                    | $>0.6$   | 1            |

3.3.3. **Boundary conditions.** In the battery box collision simulation, the rigid wall is set as a fixed constraint, and the battery box is set to collide with the rigid wall at an initial speed of 50km/h in the X direction. During the collision, there is no friction contact between the shell and the rigid wall, and no friction constraint between the monomers and the case.

3.4. **Battery failure judgment**

The two main parameters to judge the failure of lithium-ion batteries are temperature and voltage. When a short circuit occurs in batteries, the temperature rises sharply, and the voltage drops sharply. J Xu et al. found that when the power was high, the voltage would not drop to zero instantaneously in case of short-circuit failure in the battery and considered that the point of voltage dip was the point of short-circuit failure of the battery [6]. For the refined model, the short-circuit failure of the battery can be judged by the deformation of each part. Y J Zhang et al. conducted a pressure test on the monomer whose results showed that as the downward displacement of the indenter increased, the battery material failure would lead to load drop, temperature rise and voltage drop. A short circuit occurred inside the battery, and the maximum deformation before failure reached 18%. When the monomer was pressed by the load perpendicular to the monomer surface, it was deformed and its deflection decreased with the increase of the distance between the loading surface and the rigid wall. The main cause of battery pack fire was the internal short circuit or thermal failure of the monomer nearest to the loading point [7].

3.5. **Monomer simulation test**

3.5.1. **Cylindrical head intrusion test.** In LS-DYNA simulation, considering the very low Poisson's ratio of lithium-ion materials, the monomer material is set according to the properties of the compressible foam material to better match the real material parameters. The loading direction is along the thickness direction. The intrusion is defined as 4mm, which is greater than 30% of the monomer thickness, and the intrusion velocity is 1mm/s. The stress in the simulation process is shown in Figure 2. With the intrusion of cylindrical head, the stress continues to increase without failure inflection point. The simulation ends in 4s, and the maximum stress is 10.057MPa. The deformation is shown in Figure 3. The most area of the battery is not supported, and there is a large resistance in the thickness direction. The component materials are layered under pressure, and there is no shear force between the layers. The damage and deformation in the length and width direction of the battery are small.
3.5.2. Ball joint intrusion test. The monomer is mainly subjected to compression stress and shear stress in thickness direction. The indenter radius is set to 15mm. The invasion direction is along the thickness direction, the intrusion is defined as 4mm, and the intrusion velocity is 1mm/s. The stress in the simulation process is shown in Figure 4. When the intrusion reaches 3mm, the maximum stress is 6.7MPa and the minimum stress is 0.43MPa, and then the minimum stress plummets to zero. The deformation is shown in Figure 5. Before 3s, the intrusion is proportional to time, and the slope is equal to the intrusion velocity. After 3s, the intrusion increases sharply. According to stress diagram and deformation diagram, it can be judged that the monomer fails at 3s and 3mm points.

To sum up, the monomer is defined as failure when the deformation reaches 3mm in the established material parameter simulation test.

4. Analysis and improvement of frontal collision simulation

4.1. Frontal impact simulation analysis of battery box
Considering that the two monomers closest to the collision location (set as No.1 and No.13) are relatively weak, and the stress and deformation of the two monomers are the same, this paper only analyzes No.1 monomer.
The deformation curve is shown in Figure 6. At 0.675ms, the battery case collides with the rigid wall, and the monomer is extruded and begins to deform. At 0.975ms, the deformation reaches 0.65mm, and then decreases slightly, which can be regarded as the self-recovery of the battery. Deformation occurs again at 1.13ms and continues to the end of simulation. At 1.5ms, the deformation reaches 2.80mm, which is 28.67% of the thickness. The deformation is very close to the failure deformation of 3mm, and exceeds 25% of the thickness, which seriously affects the battery safety. The stress curve is shown in Figure 7. At 0.675ms, the extrusion began, and the stress increased. The maximum stress reaches 18.67MPa, which is larger than 6.7MPa concluded in the ball joint test.

The deformation curve of the battery case is shown in Figure 8. Battery case begins to deform at 0.675ms and the deformation gradually increases. When it reaches 2.23mm, the deformation decreases for a short time, and then continues to increase. At the end of the simulation, the deformation reaches 2.91mm, about 300% of the thickness. The deformation is obviously too large. The stress curve is shown in Figure 9. After contact, the stress increases continuously, and drops sharply when it reaches 1441MPa. The curve fluctuates greatly.

The curves of kinetic energy, internal energy, total energy and hourglass energy of the model during collision are shown in Figure 10. When the battery case collides with the rigid wall at 0.675ms, the kinetic energy decreases gradually, and the internal energy increases rapidly, both reaching steady state eventually. The total energy of the system is 823J, and the curve is almost unchanged without great change or mutation, which conforms to the principle of energy conservation. The hourglass energy is small during the whole process of collision, and the maximum value of 3.2J is about 0.4% of the
maximum value of the total energy, accounting for less than 10% of the total energy, which meets the requirements.

During the collision, the deformation of the monomer reaches more than 25%, and the stress is quite large. The stress-strain curve fluctuates several times. It indicates that the battery case is seriously damaged and deformed due to shaking, so it’s necessary to improve the battery case.

4.2. Battery pack safety optimization based on frontal collision

4.2.1. Optimization method
(1) Add cushion structure. Considering that the foam has low hardness and high resilience, which can absorb stress, play the role of heat insulation, inhibit thermal diffusion, and have a good flame retardant effect, EVA foam is pasted on the front and rear sides of the battery monomer, as is shown in Figure 11, which has the effect of cushioning and shock absorption. The foam size is 90mm×30mm×2mm.

4.2.2. Safety analysis. Re-analyze the improved model and compare the monomer deformation after adding EVA foam with that before improvement, as is shown in Figure 12. At 0.675ms, battery case collides with rigid wall and the monomer is squeezed. At the beginning, the deformation rate of the improved monomer is obviously reduced. The deformation at 0.6mm is equal to that before improvement, and then continues to increase until it reaches 1.88mm when the simulation ends. The maximum deformation after improvement is 2.09mm less than 2.80mm. It can be concluded that EVA foam effectively reduces the deformation rate of battery monomers and plays a buffering role. At the same time, the deformation is reduced by 8.2%, which has a certain protective effect.
Figure 12. Deformation comparison curve of battery monomer with and without cushion structure

The deformation comparison curve of the battery case before and after optimization is shown in Figure 13. Deformation begins after collision at 0.675ms. After optimization, the deformation rate of the battery case and the overall deformation trend are almost the same as that before optimization. The optimized layering thickness is 2.8mm. The maximum deformation reaches 4.9mm, and the deformation is 175%, while the maximum deformation of the original steel battery case reaches 2.9mm, the deformation is nearly 300%. It can be concluded that the deformation is reduced after material replacement.

The stress comparison curve of battery case before and after optimization is shown in Figure 14. The slope of stress rise curve after optimization is almost the same as before after collision at 0.675ms. When the first stress peak value is reached, the stress value after optimization is 720.8MPa, which is slightly higher than the 625.2MPa before. Then the stress value of the case after optimization fluctuates around 600MPa, while the stress increases to 1441MPa and then fluctuates obviously before. It can be concluded that the optimized case reduces the maximum stress value without obvious failure.

The comparison curve of monomer deformation before and after optimization is shown in Figure 15. The monomer is squeezed after the collision. Both deformations increase continuously, and the trends are almost the same. The maximum deformation of No.1 monomer is 1.56mm, which is 12.65% lower than before at the end of simulation. Therefore, the collision safety of the optimized battery box has been improved, and the safety protection of the battery has been enhanced.
5. Conclusions
This project carries out simulation according to the relevant provisions of frontal 100% collision overlapping rigid barrier test in C-NCAP. The finite element model of battery case is established and its safety in frontal collision is analyzed emphatically which can be improved by adding cushion structure such as EVA foam and replacing steel with carbon fiber composite. The maximum deformation of monomer is reduced by 8.2% by adding EVA foam, and by replacing case material, the maximum deformation of monomer is reduced by 12.65%, which effectively reduces the deformation in collision and reduces the accident rate due to battery failure. It provides an important reference for major vehicle enterprises in terms of battery safety protection measures in the future.

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