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Finite Element Analysis of Power Battery Bottom Crash in Battery Vehicles

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Declaration

This thesis is the sole work of the author and is the result of original research. All works completed have been done so by the author, using resources from University of Wales Trinity Saint David and/or Project Partner Organizations. It has not been previously submitted for examination which has led to the award of a degree.

Signed: 

Date: 02/09/2024

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Abstract

At present, all countries around the world are facing the problem of serious environmental pollution, so electric vehicles have become one of the global development trends in replacing traditional fuel vehicles. However, the development of new technologies inevitably brings new challenges and problems, and the safety of electric vehicles is crucial. In this study, characterisation and parametric modelling of obstacles for bottom crash of electric vehicles were firstly carried out. Advanced numerical techniques (FEA) are used to develop a finite element model of an electric vehicle power battery pack, which is validated by modal analysis. Subsequently, the damage analysis of the bottom crash of the battery pack is carried out and the effects of material composition and shell thickness on the crashing resistance of the battery pack are investigated. The results show that when the battery pack is subjected to bottom crash, the overall vertical displacement is large, and there is obvious plastic deformation of the bottom shell of the battery pack. Optimisation of the bottom case design can significantly improve the crashing resistance and reduce the risk of serious damage to internal components in a crash. Future work could be extended to carbon fibres, composites, etc., and even neural networks could be used to find the optimal parameters. This study provides valuable insights to improve the safety and durability of electric vehicle battery packs, which will help advance the development of electric vehicle technology

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1 Introduction

As the level of society and economy rises and the process of urban modernisation advances, the problems of energy consumption and environmental pollution have become a common challenge for all countries in the world. In order to reduce energy consumption, such as oil, and to prevent climate crises such as global warming, governments, institutions and organizations are constantly analysing and discussing the issue, and formulating restrictive policies such as carbon neutrality and carbon emissions (Tamme and Beck, 2021). In order to improve the current situation, it is the responsibility of all industrial sectors and everyone on the planet to reduce energy consumption, especially in the automotive industry. Conventional vehicles are powered mainly by petroleum processed products, which release large amounts of carbon dioxide, nitrogen oxides and other harmful gases when burned. The market for conventional internal combustion engine (ICE) vehicles has become slow to develop. As shown in Figure 1-1, fewer and fewer ICE vehicle models are being supplied.

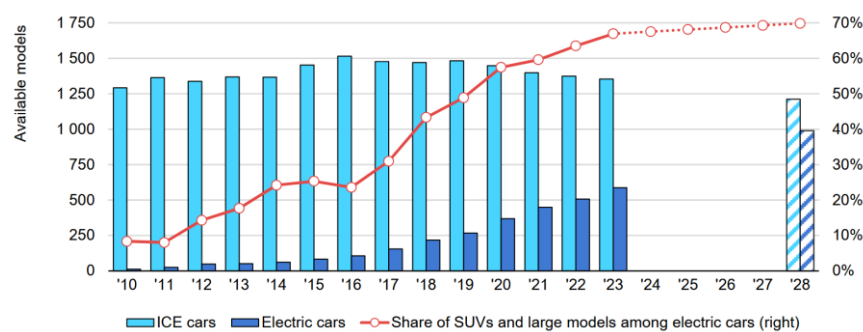


Figure 1-1: Car model availability by powertrain over 2010-2023("Global EV Outlook 2024," 2024)

Therefore, in the automotive industry, the goal of reducing carbon emissions puts enormous pressure on car manufacturers to develop the vehicles to meet environmental targets in the future. Electric vehicles have become a key focus of the automotive industry due to their excellent characteristics such as zero emissions and high efficiency. There are more than just electric cars that have the same advantages, such as hydrogen cars. However, according to the data in Figure 1-2, over the past few years, the world's investment in hydrogen research and development has been declining since 2008.

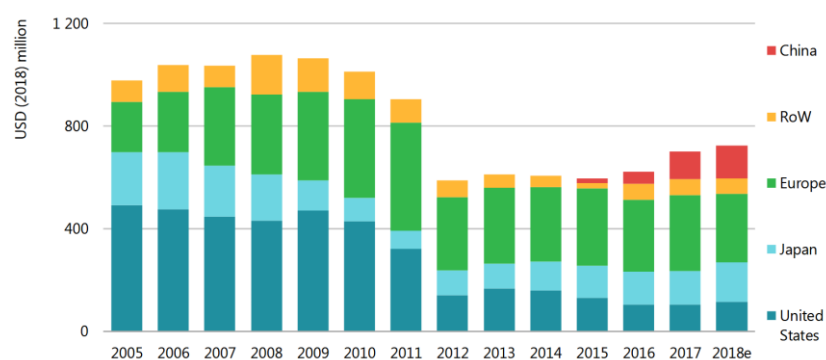


Figure 1-2: Government budgets for hydrogen

The manufacture and use of electric vehicles is increasing rapidly worldwide. According to international energy statistics("Global EV Outlook 2024," 2024) In 2023, about 14 million electric vehicles were sold globally, and this is expected to reach about 17 million by the end of 2024, which will account for more than one-fifth of global vehicle sales.

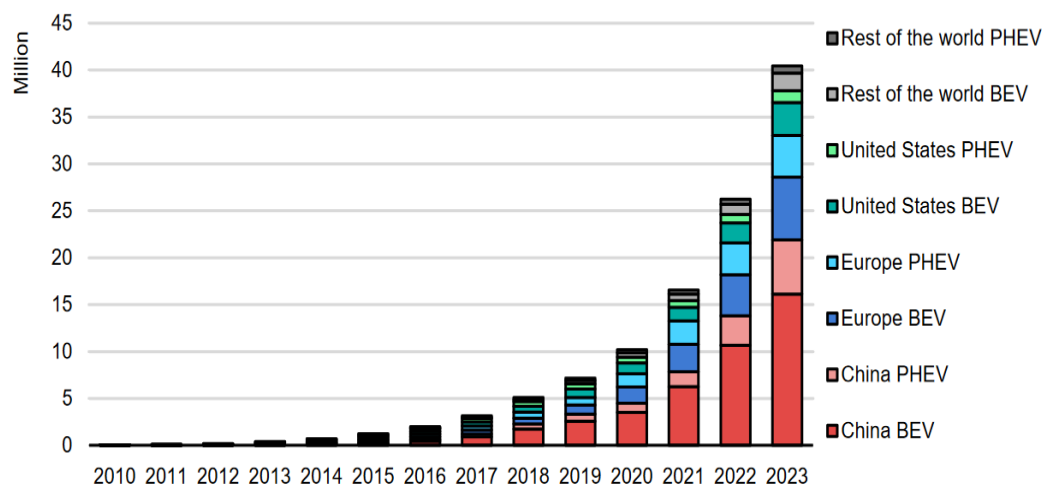


Figure 1-3: Global electric car stock trends

Electric vehicles have become a hotspot for the development of the automotive industry. The development of new technologies, however, is bound to have drawbacks and risks. Compared with conventional cars, electric vehicles have completely changed the power source, replacing the internal combustion engine with a power battery system and highly integrating the electrical control system. Batteries are flammable and explosive, and environmental changes such as temperature rise, short circuits and impacts can cause thermal runaway of batteries, which can lead to fire or even explosion. Therefore, the improvement of the crash safety performance of electric vehicles has become an urgent problem, governments and organizations around the world have been continuously developing and improving the standards for electric vehicles and sub-systems in order to reduce risks.

Battery packs, as an important subsystem of electric vehicles, are generally installed at the bottom of the vehicle. It's good for lowering the centre of gravity of the car (Synák et al., 2023). However, it greatly increases the likelihood of underbody collisions at the same time. When an electric vehicle is faced with driving on a potholed road, rocks on the road, or falling objects from the vehicle in front of it, the obstacles are prone to collide with the bottom of the vehicle. The battery box, as the mechanical structure of the battery system, is the first to be impacted by the load (Liu et al., 2020). If its mechanical properties do not meet the requirements, it will lead to deformation of internal parts, triggering the internal electrochemical reaction of the battery cell, and the consequences are very serious (Zhang et al., 2018). In addition, the existing crash test standards do not set out detailed criteria for the bottom crash of electric vehicles. Therefore, it is necessary to test the battery pack in a virtual environment through finite element analysis to optimise product design and reduce the cost of manufacturing and testing.

1.1 Aim and Objectives

1.1.1 Aim

The aim of this work is to study the impacts caused by bottom impacts on electric vehicle power batteries and to assess the structural strength and impact resistance of power battery packs by using modern numerical techniques, especially finite element simulation analysis. At the same time, the bottom of the battery pack is optimally designed to improve its impact resistance.

1.1.2 Objectives

The research in this work has the following objectives;

1. Analyse different scenarios causing impacts at the bottom of battery packs in electric vehicles, and carry out theoretical analysis and finite element modelling of bottom obstacles.
2. Establishing a finite element model of an electric vehicle battery pack and Performing modal analysis to validate the model.
3. Battery pack bottom impact finite element simulation analysis.
 - i. Analysing damage to electric vehicle battery packs after bottom crashes
 - ii. Investigating the effect of the material and thickness of the battery pack backshell on impact resistance

1.2 Thesis Organizations

The structure of this report is as follows: Chapter 2 provides a literature review of electric vehicle power battery systems. Chapter 3 provides a detailed analysis of obstacles on the road, including the types of obstacles and the form of contact between the obstacles and the bottom of the vehicle. Chapter 4 carries out finite element analysis of the battery pack, including modal analysis and bottom crash damage. Chapter 5 investigates the effect of different materials and thicknesses on the crashworthiness of the battery pack. Chapter 6 provides suggestions for future work, some of which are ongoing. Chapter 7 concludes the report.

1.3 Research Methodology

The methodology used in this project consists of six main steps:

- 1) Start with a literature review and analyse the trends and shortcomings of current research.
- 2) Determine the modelling method based on the analysis of obstacles.
- 3) Finite element modelling of the battery pack.
- 4) Conduct modal analysis of the finite element model to determine the reliability of the model.
- 5) Perform a finite element analysis of the bottom crash of the battery pack.
- 6) Determine the effect of different battery pack bottom shell materials and thicknesses on impact resistance.

2 Literature Review

This part of the report focuses on the research development of power battery systems for electric vehicles (EVs), including dynamic response and finite element (FE) modelling of EV single cells, battery packs under mechanical abuse behaviour, and the optimal design of power battery packs for EVs.

2.1 Single Cell

The cell is the main component of the power battery system of electric vehicles, and its durability and safety are crucial. During vehicle travelling, the power battery will be subject to various load conditions such as vibration, collision and shock load. Mechanical deformation caused by loads can lead to contact between the positive and negative terminals of the battery, causing battery short-circuit failures and, in extreme cases, fires. Over the decades, scholars have conducted extensive research on the effects of mechanical abuse on single batteries. (Kermani and Sahraei, 2017) provided a comprehensive review of advances in mechanical testing and modelling of different types of lithium-ion batteries under mechanically abusive loading scenarios, focusing on the mechanical properties of the battery cells. Currently, depending on the manufacturer, there are two main different forms of single batteries used in automobiles (cylindrical and pouch).

2.1.1 Cylindrical Cell

Cylindrical lithium-ion batteries (LIBs) consist of (i) jelly roll, wound composite material consisting of a cathode, an anode, and two diaphragms, and (ii) battery casing consisting of a jar and lid. Cylindrical battery are favoured by Tesla due to its structural stability and mature production technology.

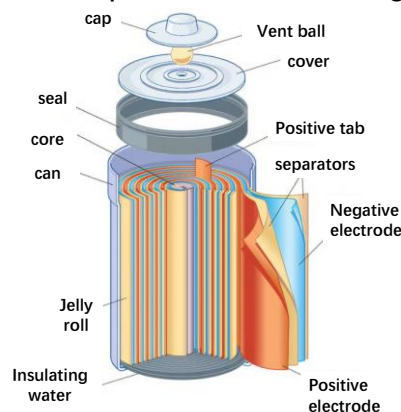


Figure 2-1: Cylindrical Cell

A comprehensive study of the safety of lithium-ion batteries in terms of crashworthiness and an investigation of the mechanical response and failure mechanisms of the batteries in case of mechanical abuse are essential. (X. Zhang et al., 2023) conducted drop hammer shock dynamic tests on classic 18650 LIBs. The results showed that, in addition to the impact energy, the dynamic response and internal failure mode of lithium-ion batteries mainly depended on the impactor

type and state of charge (SOC). With the increase of SOC, the peak force and failure temperature of the battery increased significantly, promoting the extension of failure cracks. The mechanical responses due to different impact velocities and impactor diameters were significantly different as analysed by FE. When the impactor diameter was less than 20 mm, the damage displacement increased with the increase of the impactor diameter. Meanwhile, the experimental results of (Moon et al., 2022) showed that as the diameter of the cylindrical indenter increased, the faster the internal short-circuit occurs in the LIB and the larger the internal short-circuit area. Further, (Huang et al., 2024) introduced an acoustic emission (AE) testing technique to explore the failure behaviour of 18650 LIBs under planar compression, local indentation and three-point bending. The whole compression process of the cell was divided into five stages based on the characteristic parameters of the force response and AE signals. Meanwhile, the data showed that under a small diameter (20 mm) indenter, the cell had a low load carrying capacity at the point of failure, and the electrical failure and temperature rise were more severe.

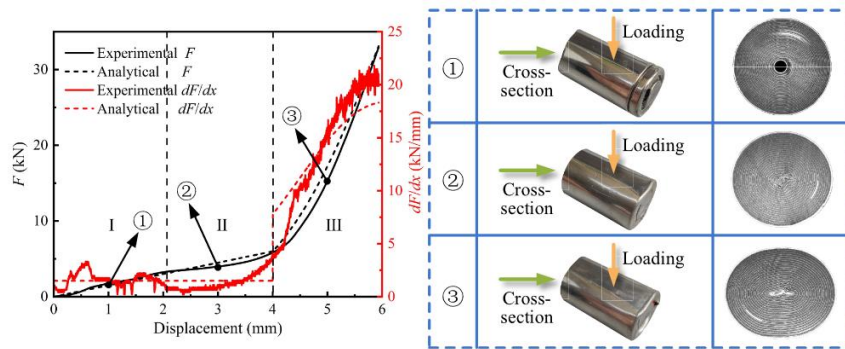


Figure 2-2: Experimental results and analytical results (Huang et al., 2024)

Similarly, the results in (An et al., 2024) found that a higher battery SOC means a faster average temperature rise rate of the battery. When the SOC was higher than 60%, the battery would experience dramatic thermal runaway. In addition, (Yang et al., 2019) found that as the battery deformation continues, the internal short circuit (ISC) of the battery evolved from a soft internal short circuit to a hard internal short circuit. A soft ISC is defined as microscopic damage indicated by no change or a slow decline of the battery terminal voltage. A hard ISC is defined as a macroscopic fracture indicated by a rapid decline of the battery terminal voltage. SOC was a key factor in determining the strength of the soft short circuit. However, vehicles are often in complex situations at high speeds. Therefore, (Yu et al., 2021) studied the mechanical properties of lithium-ion batteries at the instant of high acceleration stamping. Through theoretical analysis and simulation calculations, it was concluded that increasing the diaphragm thickness and increasing the elastic modulus were the optimal design methods for lithium-ion batteries.

In order to better study the response of the battery in mechanical abuse, building an FE model for simulation calculation is one of the economical and efficient methods. (Sahraei et al., 2012a) carried out four different loading tests on 18650 cylindrical cells. A homogenised and isotropic FE model was developed, which can accurately capture the global response of the cell under the four different

loading conditions. In their later work, (Sahraei et al., 2015) in order to predict the crack extension of lithium-ion batteries under mechanical loading, an anisotropic model was developed, which improved the ability to predict the direction of cracks. Moreover, (Zhu et al., 2016) considered the laminar structure of the cells and the anisotropy of the cellular components to establish a detailed axisymmetric 3D finite element model, and the simulation results were in good agreement with the experimental results. (Greve and Fehrenbach, 2012) proposed a generalised plasticity model to simulate the homogenised isotropic response of jelly roll cake, and the load-displacement curves obtained from the simulation were very close to the experimental results. In contrast, (Gilaki and Avdeev, 2016) developed a heterogeneous finite element model in LS - DYNA. The deformation shapes, impact velocities and impact loads obtained from the non-homogeneous simulation were compared with the results of the homogeneous simulation, which were in good agreement.

2.1.2 Pouch Cell

Soft pack batteries usually consist of a positive electrode, a negative electrode, a diaphragm and a soft packaging material. They are popular with automakers such as Chevy and Nissan due to their high safety and light weight. (Sahraei et al., 2012b) conducted mechanical tests on LiCoO₂/graphite small pouch cells in through-thickness compression, in-plane unconfined compression, in-plane confined compression, hemispherical punch indentation and three-point bending. The experiments showed that the cells have a very low Poisson's ratio. Therefore, it was appropriate to use the foam model to simulate the deformation behaviour. Besides, the design of the shell would affect the overall strength of the cells under certain loading scenarios. (Kisters et al., 2017) tested dynamic partial indentation of pouch batteries in the velocity range of 0.01 mm / s ~ 5 m / s. The results of the dynamic indentation tests showed that the failure limit of pouch batteries was low and that the failure limit of pouch batteries should be estimated. The results indicated that the critical load of the soft pouch battery is low and the failure limit of the battery cell should be estimated in the dynamic test. Hence, (Chen et al., 2019) made a dynamic test of lithium-ion soft pack battery under high speed (200 ~ 1000 m / s) impact. The dynamic response is shown in Figure 2-3. The simulation results showed that the internal interface state between the cell components is an important factor in determining the diffusion or absorption of impact energy. Compared with the quasi-static tests, the mechanical response of the pouch cell was independent of the set far-field boundary conditions.

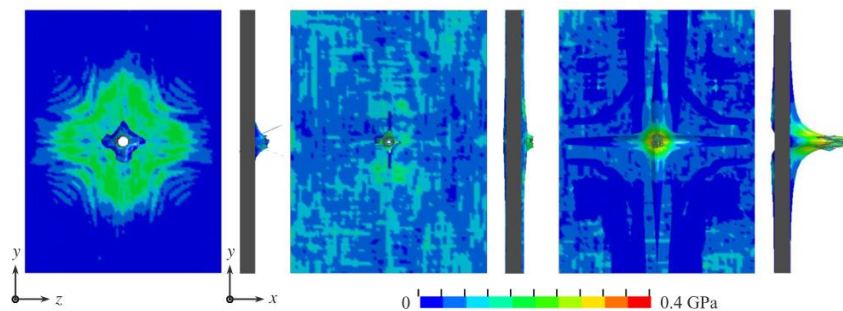


Figure 2-3: Dynamic mechanical response of the pouch cell(Chen et al., 2019)

With regard to FE modelling of soft-pack batteries, (Tancogne-Dejean and Mohr, 2022) found that simulations using an isotropic plasticity model were fully capable of providing reasonable predictions of the force-displacement curves for a series of indentation experiments. This was due to the extremely high aspect ratio of the metal collector foils. In the same way, (Arief Budiman et al., 2022) used a homogenised soft pack cell model for the simulation of three-point bending tests. Force-displacement curves consistent with the test results were obtained with low simulation cost and high time efficiency.

2.2 Battery Pack

The power battery is the 'heart' of an electric vehicle and is usually mounted on the vehicle body in the form of a battery pack or battery box. The entire battery module consists of complex structures and composites with significant geometries and material non-linearities.

2.2.1 Battery Pack Placement

The placement of the power battery pack is usually based on the overall spatial structure and layout of the electric vehicle to carry out a reasonable arrangement. At the same time, the placement of the battery pack also needs to take into account the driving form of the electric vehicle, load matching and battery pack ground clearance and other factors. As shown in Figure 2-4, the placement of the battery pack mainly includes rear and centre. The first one will make the whole vehicle centre of mass shifted back, when the battery pack mass is large, it will seriously affect the operation stability of the electric vehicle. If the mass of the battery pack is limited, its capacity becomes less, which greatly limits the range of the electric vehicle. Whether the battery pack is integrated into the chassis (skateboard chassis) or the battery pack is placed under the base plate, the battery pack will be placed in the centre of the vehicle. The advantage of this is that it maximises the use of space for larger and more modular power packs. Moreover, due to the addition of battery packs, the whole vehicle centre of mass is moved down, which effectively improves the electric vehicle stability and vehicle dynamics. At the same time, this arrangement can effectively improve the safety performance of electric vehicles during frontal or side collisions. Both are attached to the body by welds and bolts. Table 2-1 shows the location of battery packs in different cars.

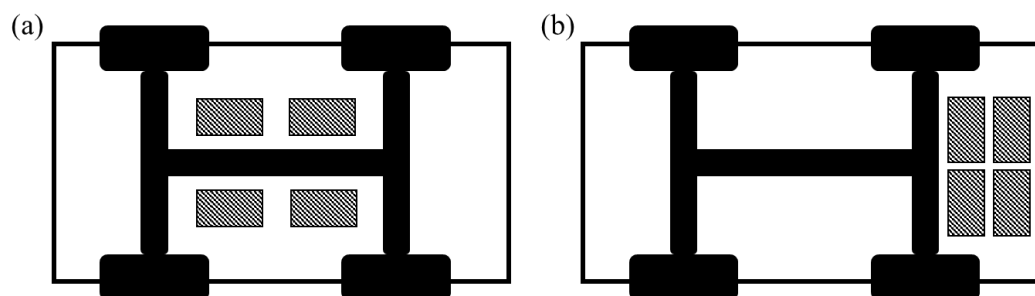


Figure 2-4: The placement of the battery pack

Table 2-1. The location of battery packs in different cars

Vehicle	Image	Type	Battery Location
BMW i3		Sedan	Centre
Nissan Leaf		Micro	Rear
Tesla Model S		Hatchback	Centre
BYD e6		Micro	Centre
Toyota RAV4		SUV	Centre
Chevrolet Spark		Micro	Rear

2.2.2 Battery Pack Structure

Although most automakers install the battery module in the centre of the vehicle, the construction varies. Without compromising vehicle dynamics and safety, there are many different battery pack configurations for electric vehicles, taking into account factors such as space utilisation, battery pack size and weight.

As shown in Figure 2-5, the Chevrolet Volt has a 'T' shaped battery pack structure consisting of four battery modules placed under the rear seats and on the access road to the front seats in order to facilitate placement of the battery pack under the floor of the vehicle. However, the Volt is still a space-constrained fuel car, which limits the size and weight of the battery pack it can carry. The rational design of the Volkswagen e-Golf battery module takes advantage of the structural features of the body, as shown in Figure 2-6.



Figure 2-5: Chevrolet Volt Battery Pack



Figure 2-6: Volkswagen e-Golf Battery Pack

The battery pack of the Nissan Leaf consists of three groups of cells as shown in Figure 2-7. It is assumed that the height of group S1 is h_1 , the height of group S2 is h_2 , and the height of group S3 is h_3 . According to the design, the heights of h_1 and h_3 are higher than the height of h_2 , so they fit perfectly into the seat floor. When viewed from the side of the vehicle, the battery modules have a 'concave' shape, which makes more efficient use of the space under the seat and increases the number of batteries. In addition, height h_3 is higher than height h_1 , so the rear seats are higher than the front seats, providing rear passengers with a wider viewing angle.

Most of the other car makers use skid plate chassis or similar design concepts. Tesla, for example, uses a modular design for the battery pack, which is placed horizontally under the chassis so that the battery pack is integrated with the chassis, maximising the use of available space. The frame is used to enhance the protection of the battery pack structure. This structure increases the vehicle's stability during various driving manoeuvres by lowering the centre of gravity. However, it also reduces the clearance between the vehicle and the ground, exposing the battery pack to the risk of ground or obstacle impact. As shown in Figure 2-8.

Traditionally, battery cells have been protected from underbody impacts by metal or plastic enclosures along with module and pack housings as well as body structures such as cross members, doors and floors. In addition, as the underbody can only withstand impacts from small stones on gravel roads, underbody impact protection is provided by 1-6 mm thick metal plates (monolithic or sandwich construction, or even a combination of both). The sheet metal is also coated with a polymerised coating for rust protection.

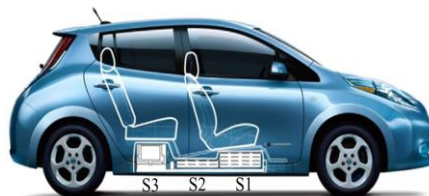


Figure 2-7: Nissan Leaf Battery Pack

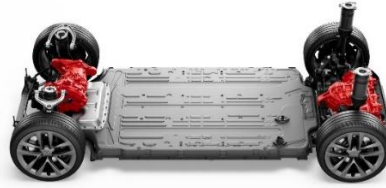


Figure 2-8: Tesla Model 'skateboard' battery pack

2.2.3 Battery Pack Safety Characteristics

Firstly, (Xia et al., 2017) conducted a series of impact tests with different combinations of loading speed, drop mass, module orientation and impactor shape from the perspective of different impact loading conditions. Figure 2-9 shows the definition of X,Y and Z axes and red lines carrying message. The results showed that in the impact tests along the X or Y direction, the battery module had a weak load-carrying capacity, and no thermal runaway occurred after the test, despite the short-circuiting of the cells. However, in the impact test along the Z direction, thermal runaway occurred in the form of fire and smoke due to the fact that it was difficult to release the heat from the battery cells. As a result, the battery module was severely shocked in the vertical direction. In particular, (Shao et al., 2022) studied the safety characteristics of the module under vertical impact conditions. Vertical dynamic impact tests were carried out on the battery module at 100 % SOC. The results showed that the contact area is smaller, the deformation of the module is larger; in addition, the closer the impact point is to the edge, the larger the deformation is, and the weaker the load-bearing capacity of the module is.

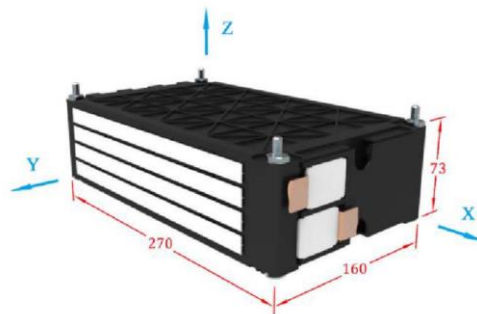


Figure 2-9: Dimensions of battery pack(Xia et al., 2017)

At the same time, the influence of components other than cells in the power battery system on the safety of the battery module is also crucial. (Kalnaus et al., 2018) conducted an extrusion experiment on a battery module in order to explore the effects of cooling plates and module protection shells on the deformation and failure of a single cell of the battery module. The results indicated that the presence of the cooling plate and module protective casing can greatly reduce the pressure on the single cell. In order to analyse the role played by the module holder in the mechanical response of the module, (Xi et al., 2022) studied the mechanical response of the battery module under static and dynamic conditions through experiments and simulations. It was found that the presence of the module holder significantly improved the distribution of the battery high-voltage

region in the module during a collision, but led to a rise in the local peak load. (Zhu et al., 2021) carried out extrusion tests at quasi-static (0.06 mm/s) and low speed (50 mm/s). It was found that the ductility of the critical components (especially the separator) was low and the cover was able to withstand large plastic deformation without fracture, which significantly improved the contact force and energy absorption. Furthermore, (Kalnaus et al., 2019) studied the mechanical behaviour of battery modules under high rate deformation. They conducted indentation tests on over 100 samples with loading rates increasing from quasi-static to high rates (1m/s). Using x-ray scanning techniques, they analysed and found that at impact velocities higher than 25cm/s, the cell stack response changed from a compressible, crushable type to a dense material characterisation. In addition, to address the problem that it is difficult to analyse the failure characteristics of small mechanical deformations, (A. Zhang et al., 2023) had provided an approach that adopts the mean normalisation method to analyse the voltage consistency of batteries under different degrees of mechanical deformations.

2.2.4 Battery Pack Optimisation

Power batteries, as the core subcomponents of electric vehicles, are usually installed on the vehicle chassis in the form of battery packs. Therefore, the optimal design technology of battery packs has become the research focus of electric vehicles. (Setiawan and Salim, 2017) conducted a finite element simulation of the side impact of an electric vehicle according to the standards of the European Organization for New Car Assessment and Safety (E-NCAP). The deformation of battery after impact is shown in Figure 2-10. In order to improve the crash safety of the battery pack, aluminium foam was used as the structural filler, which successfully reduced the deformation of the battery pack.

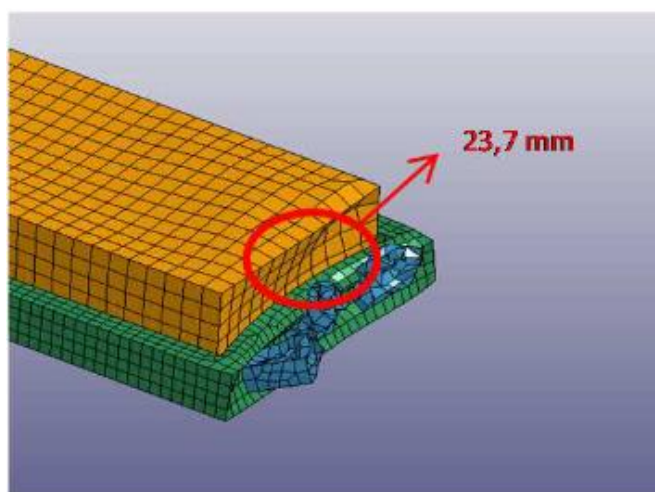


Figure 2-10: Deformation of battery and protector (Setiawan and Salim, 2017)

(Pan et al., 2022) developed a dynamic model of the battery pack casing and performed modal validation in order to evaluate the crashworthiness of the battery pack casing. The optimised design of the battery pack casing and lugs resulted in a weight reduction of 2.9 kg (20.6%) and 0.578 kg (8.2%) for the bottom casing and lugs, respectively, but the crashworthiness was effectively improved. (Li et al.,

2024) optimised the design of the battery pack chassis based on a honeycomb structure. A nonlinear finite element model was established and validated for crash simulation. The results showed that the optimised bionic honeycomb structure could reduce the deformation of the battery pack bottom case by 30% and the maximum stress by 10% when the thickness was 1 mm and the number of replacement hexagons was 2 and 4. (H. Wang et al., 2024) built a finite element model of the battery pack and a crash-resistant model of the compression machine. Combining the genetic algorithm, contribution analysis and other method, the optimal design of the battery pack bottom case was carried out with the thickness as the design variable, which finally reduced the total weight of the battery pack by 4.31% and the crushing deformation of the case by 5.97%. (W. Wang et al., 2024) designed a new power battery pack with a three-dimensional (3D) star-assisted structure, which has a smaller intrusion displacement and a larger energy absorption ratio than the conventional design. All these studies are useful references for the safety design of electric vehicles.

2.2.5 Conclusion taken from literature review

With the gradual increase in the use of electric vehicles, scholars are paying more and more attention to the battery pack of electric vehicles. From the existing literature, it can be mainly divided into 2 levels. Level 1 is mainly for the study of single battery, such as the mechanical characteristics of battery cell failure short-circuit, the improvement of battery energy density, and the impact of SOC of battery power on the mechanical characteristics of the battery, etc. Level 2 is mainly for the study of the whole battery pack, the research direction is mainly focused on the battery pack collision, how to improve the battery's crashworthiness at the same time lightweight and battery thermal stability and safety, etc. In reviewing the results achieved by various scholars at the same time, there are still some aspects of in-depth research can be carried out, specifically as follows:

- a) For the battery cell, the tests are mainly radial extrusion, pinning and three-point bending. However, when an electric vehicle collides with an obstacle, the battery pack receives impact loads in the vertical direction, so it is necessary to study the vertical impact. The testing in this report is similar to the work carried out by Pan, because their research is also the optimisation of the bottom shell based on impact, however they suggested that special attention should be paid to impact damage in the vertical direction so this is done
- b) There is no unified test guideline or safety specification for the underbody collision of new energy vehicles, and due to the complexity of the mechanism of collision in this type of working condition, there is a lack of sufficient collision database support, and insufficient research on the collision between this type of on-board power battery pack and obstacles.

3 Analysis and Modelling of Road Obstacles

3.1 Background

Power battery pack, as the main energy source of electric vehicles, is installed at the bottom of electric vehicles, which often causes great traffic accidents when electric vehicles travelling on the road at a certain speed have impact collisions with obstacles. In order to study the bottom collision between obstacles and battery packs, the obstacles on the road are firstly collected and classified, and the geometrical shapes and collision forms of obstacles are summarised, so as to establish a parametric model of obstacles.

3.2 Types of Road Obstacles

Obstacles such as tyres, stones, and falling objects from other vehicles are often on the road when vehicles are in motion. Between 1995 and 2003, the American Automobile Association Foundation for Traffic Safety conducted a survey of obstacles on the road (Forbes & Robinson, 2004). The results showed that obstacles include substances, materials, and objects that interfere with the normal road environment. They may be created by vehicles or other sources. In practice, obstacles on the road are considered to be litter. For example, in 2000, a study of litter in Washington State reported that tyres were the largest type of trash on interstate highways, accounting for nearly 25 %. Metal and plastic car parts accounted for more than 8 %, and other items (rocks, wood products, other metals and composites and organic materials) combined accounted for nearly 40 % (Brian C. Tefft, 2016). Different obstacles are shown in Figure 3-1. The sources of roadside foreign matter can be divided into three main categories:

- (1) Vehicle parts that fall off while the vehicle is in motion and items that fall off the cargo, mainly including: tyres, bumpers, wings, steel plate springs, and so on. Lorries are also loaded with incomplete cargoes, resulting in the fall of cargoes, such as: furniture, wood, steel pipes, etc.
- (2) Rocks rolled down from mountains. Due to atmospheric conditions, rainfall and other factors, landslides often cause various kinds of rocks to roll onto the road; some lorries loaded with rocks may also cause rocks to fall onto the driveway due to the instability of the vehicle.
- (3) Road fixtures. Roads are often fitted with speed bumps to prevent vehicles from travelling too fast, and some speed bumps are as high as 15 cm, which can cause electric vehicles with low chassis to bottom out, and some roads are also fitted with barriers.



Figure 3-1: Types of obstacle

Traffic accidents caused by obstacle objects can be seen everywhere. In 2019, a tyre that came off from a front car and fell on a highway caused a tragic multi-vehicle collision in which one person was killed. In the same year, the Tesla Model S hit a rock on the road while driving fast, and the rapid impact penetrated the battery pack case, causing the entire battery module to be damaged and fire. Collisions between cars travelling at high speeds on roads and obstacles are the focus of media attention in various countries. Once an accident occurs, it could cause property damage or even threaten human lives. (Brian C. Tefft, 2016) reported that American Automobile Association Foundation for Traffic Safety conducted a study on motor vehicle crashes caused by road debris based on statistics from the National Highway Traffic Safety Administration. In 2001, debris deposited on roadways was responsible for approximately 25,000 crashes, resulting in 81-90 deaths in 2001 (Forbes & Robinson, 2004). Between 2011 and 2014, debris-related crashes were approximately 4 times more likely to occur on interstate highways compared to crashes not debris-related crashes, Specific statistics are shown in Table 3-1. During this three-year period, an average of 35,000 vehicle collisions per year were caused by obstacles on the road, resulting in 7,500 injuries and 90 deaths per year.

Table 3-1. Characteristics of different crashes (Brian C. Tefft, 2016)

		Crashes	
		Debris-Related	Non-Debris-Related
		<i>Weighted Column %</i>	
Road type			
	Interstate highway	33.4	8.4
	Other road type	66.6	91.6
Atmospheric conditions			
	Rain	10.9	9.5
	Sleet/hail/freezing rain	0.4	0.7
	Snow	1.2	3.4
	Fog	0.6	0.4
	Other conditions	2.3	0.2
	No adverse conditions	85.2	86.1
Time of day			
	6:00 AM - 9:59 AM	14.9	17.3
	10:00AM - 3:59 PM	35.6	35.3
	4:00PM - 8:59 PM	29.5	31.7
	9:00 PM - 5:59 AM	20.1	15.7
Maximum injury severity in crash			
	Property damage (no injury)	85.6	71.2
	Injured	14.2	28.3
	Killed	0.2	0.5

3.3 Types of Contact

As there are different obstacles on the road, there are different types of contact they make when they collide with the underside of a car. They can be categorised into three main types:

a) Face-face contact

Face-face contact is when a vehicle chassis encounters an obstacle with a large contact area, such as a raised stone or wood block on the road surface during travel. This can result in a damaged chassis deformation, but without a large stress concentration. This is shown in the figure. This type of damage does not cause a lot of damage, but for a conventional fuel vehicle it may cause the fuel tank to fracture, resulting in a leakage of fuel, and for an electric vehicle it may cause deformation of the power battery located at the bottom of the vehicle.

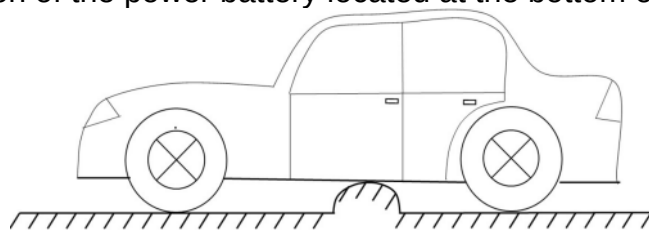


Figure 3-2: Face-face contact between car and obstacle

b) Line-face contact

Line-plane contact is mainly due to obstacles with long edges and corners, e.g., metal products, speed bumps. Or it may happen when the car is going up and down the steps, due to the high height of the road step, the bottom of the vehicle is rubbed and scraped by the corners of the road step. According to the severity of damage, scuffing on the underside of the vehicle can be classified into minor scuffing and serious scuffing. Minor scuffing usually only causes damage to the surface of metal or plastic parts of the chassis of the vehicle, which does not significantly affect the operation of the vehicle, while serious scuffing will damage the structure of the components of the chassis of the vehicle, resulting in deformation of the chassis, which affects the normal operation of the vehicle. Figure 3-3 illustrates the situation of line-plane contact.

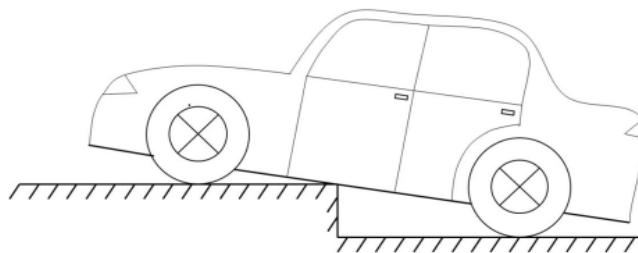


Figure 3-3: Line-face contact between car and obstacle

c) Point- face contact

Point - surface contact is due to the car in the process of high-speed driving, the vehicle rolled up sharp obstacles caused by the chassis puncture. Or due to uneven road bumps, the vehicle wheels sink, the car chassis pierced by obstacles, as shown in Figure 3-4. Among these three types of collision conditions, this causes the most damage to the vehicle, especially for electric vehicles. The most of battery are arranged at the bottom of electrical vehicle. This can cause a puncture in the vehicle's chassis, which can cause a puncture in the power battery, leading to thermal runaway of the battery and an electric vehicle fire.

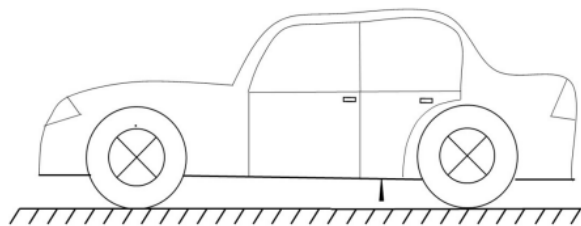


Figure 3-4: Point-face contact between car and obstacle

Obviously, when the vehicle travelling speed is the same and the obstacle has the same force on the bottom of the vehicle, point- face contact has the smallest contact area, so the puncture caused by the point-face contact forms the deepest depression in the chassis of the vehicle, which is the most destructive to the body of the vehicle. Due to the large contact area of line-plane contact and surface-plane contact, the depth of the depression caused by the undercarriage is not as deep as that caused by point-plane contact. For electric vehicles, the greater the depth of the bottom puncture, the more likely to cause deformation and rupture of the power battery, which is more likely to cause electric vehicle safety accidents.

Therefore, the point-surface contact type collision is chosen to investigate the collision at the bottom of the power battery pack of electric vehicles.

3.4 Modeling of Obstacle

The geometric characterisation of the obstacle and the definition of the ground impact form is the more difficult part, as there is less literature and information on related studies such as ground collision impact and obstacle modelling for battery packs. Therefore, this work refer to the collision analysis of a ship sailing in the sea with a submarine reef. (Leira, 2013)] proposed a simpler model for submarine reefs, the polynomial model, with the following expression:

$$z = -\frac{y^2}{a}$$

Where a is the rock shape parameter for the four different rock sizes shown in Figure 3-5, the shape of the whole body is controlled by adjusting the value of a . When a is larger, the simulated rocks are blunter, as shown in the black curve in the figure, and when a is smaller, the simulated rocks are sharper, as shown in the green line in the figure.

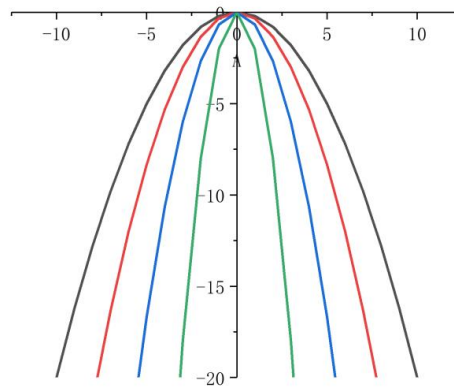


Figure 3-5: Stone polynomial model

(Sormunen et al., 2016) proposed a double orthotropic function model to describe the shape of a submarine reef with the following expression:

$$Z = b_0 \frac{1}{2\pi\sigma_x\sigma_y\sqrt{(1-\rho)^2}} \exp\left(-\frac{1}{2(1-\rho^2)}\left(\frac{(x-\mu_x)^2}{\sigma_x^2} + \frac{(y-\mu_y)^2}{\sigma_y^2} - \frac{2\rho(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y}\right)\right) - b_1$$

Where b_0 is the scale multiplier, b_1 is a constant that cancels out all observed errors, σ is the standard deviation, μ is the mean, and ρ is the correlation between x and y . The shape of the reef is fitted by adjusting the parameters of x , y , the bias and the variation of the homogeneity. The goodness of the fit was evaluated using the coefficient of determination R^2 , which has a best possible value of 1. The model is shown in Figure 3-6.

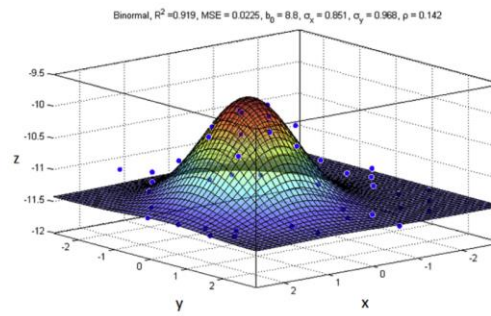


Figure 3-6: Example of a rock with binormal fit with $R^2 = 0.92$.

(Rawson, 1998.) proposed a cone model, he found that the size of the stones is not only different in the size of the cone angle, but also the radius of the tip of each stone is not the same, and proposed a cone model of the stones in the form of three parameters, i.e., the overall height of the stone (H), the radius of the tip (R), and the angle of the cone (β), as shown in Figure 3-7

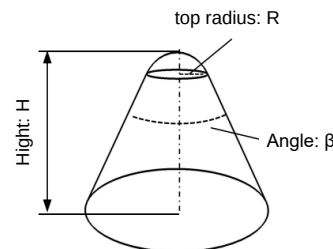


Figure 3-7: Cone Model

The modelling should not only take into account the shape characteristics of the obstacles, but this should be operational for the subsequent simulation calculations. Based on the above research, this work adopts stone blocks, which account for the largest proportion of obstacles on the road, for the study. Combining the characteristics of stones on the road and the contact form of the point-face type, in this work, the cone model is used to model and analyse the obstacle of the vehicle bottom collision. The three parameters of the model reflect the general characteristics of the stones. By adjusting the parameters it is possible to regulate the shape and size of the obstacle, which can also be investigated in more depth in future work.

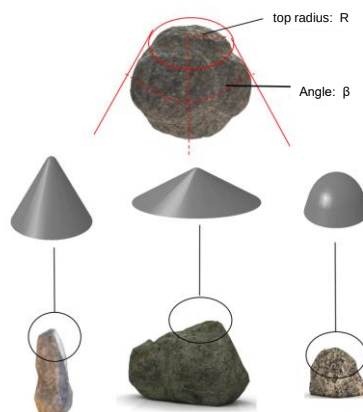


Figure 3-8: Parametric modelling of stone blocks

4 FEA of Power Battery Bottom Crash in Electric Vehicles

Finite Element Analysis (FEA) is a highly efficient and commonly used numerical method for finding approximate solutions to complex partial differential equations. Its basic idea is to discretely divide the region of the equation into several cells or grids, and under the premise of satisfying all or part of the boundary function, find the approximate solution of the partial differential equation by 'discrete approximation', thus making a continuous infinite degree of freedom problem into a discrete finite degree of freedom problem. At present, the finite element method is mainly used to solve three aspects of computation: the establishment of the mathematical model of the research object, the selection of reliable numerical algorithms, and the analysis of the results of the calculations. The finite element method is an advanced means and a reliable tool for solving all kinds of complex problems in both scientific research and engineering technology (Marinkovic and Zehn, 2019).

4.1 FE Model of Power Battery Pack

FEA is a computational model that provides the raw data for finite element analysis and is composed of four types of data: nodes, cells (grids), material properties and boundary conditions. It can accurately describe the physical and geometrical characteristics of the actual object, and the results calculated by the finite element method have a greater reference value and significance. Therefore, the correct establishment of the finite element model is a key step in the finite element analysis, and the modelling process can be divided into the following steps: simplification of the three dimensional (3D) model, geometric clean-up, meshing, definition of the material properties, and setting of the boundary conditions, as shown in Figure 4-1.

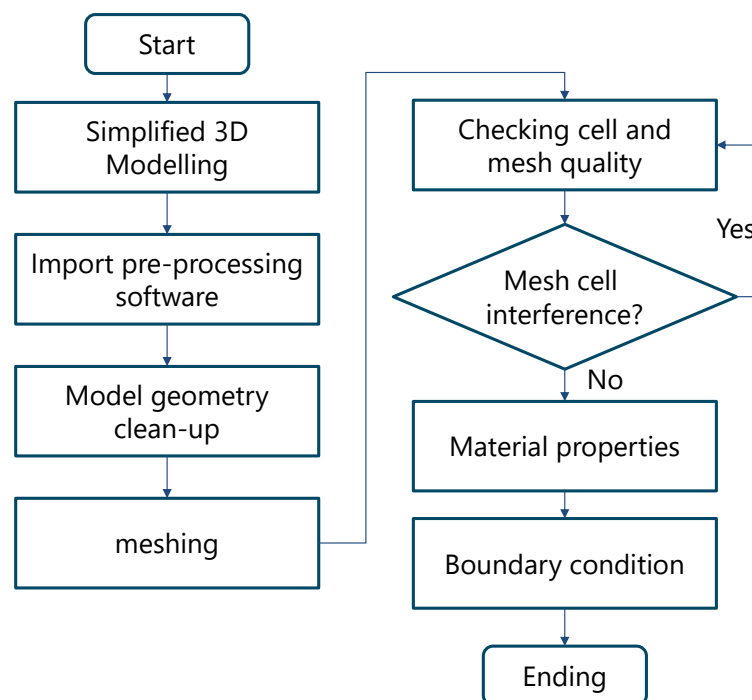


Figure 4-1: FEA process

4.1.1 3D Model

In this work, a typical battery pack is adopted. As mentioned in section 2.2.1, the battery pack is located in the centre of the vehicle. The battery pack adopts 3750 NCR18650 type lithium-ion battery cells. The basic framework of the power battery pack is formed by the structure form of 50 parallel and 75 series. The power battery pack is installed under the chassis of the car. The internal structure of the battery pack is 5 battery modules of the same specifications, using liquid cooling cooling method, waterproof and dustproof sealing grade IP67. The CAD model of the battery pack is downloaded online. The internal structure of the battery pack is shown in Figure 4-2. The power battery pack consists of five parts, which are structural component system, power battery module system, battery management system (BMS), battery thermal management system, and electrical system. Each part works together to form a complex system integrating mechanical, chemical and electrical components. The structural component system mainly consists of the top shell, internal bracket, lifting ear, mounting brackets, trays and bottom shell. The main role of the battery management system (BMS) is to real-time monitor each individual battery, including battery voltage, current and temperature parameters. At the same time, it prevents the battery from over-discharging by cutting off the current when the battery is discharged to a certain level. When the battery is full, it cuts off charging and prevents overcharging to improve battery life and increase the safety performance of the battery; the battery thermal management system mainly consists of water-cooling boards, fans and heat-conducting pads, etc., whose main function is to regulate the temperature inside the battery pack and improve the reliability of the battery's performance; the electrical system mainly consists of relays, high-voltage and low-voltage line speeds, and insurance devices, etc., for real-time detection and transmission of signals.

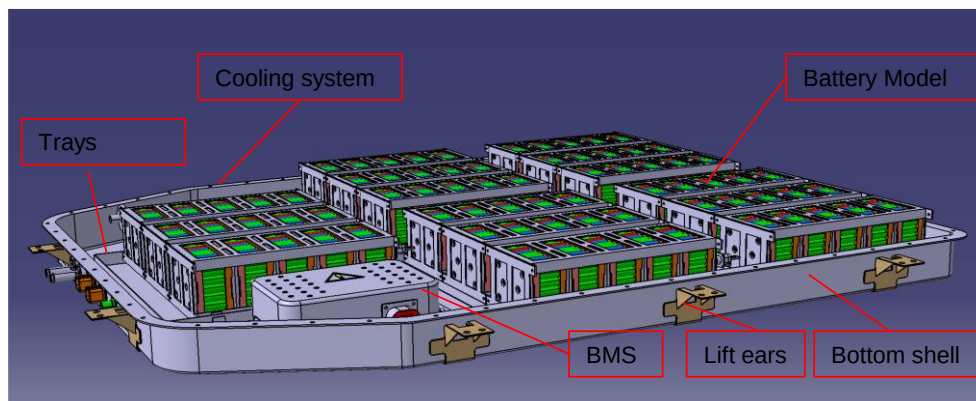


Figure 4-2: 3D model of battery pack

4.1.2 Geometric clean-up

Power battery pack is composed of thermal management system, electrical system, monitoring system and other systems. There are many structurally complex parts in each system. If these complex non-structural parts are subjected to finite element analysis, it will not only fail to improve the accuracy of the calculation results, but also lead to a great increase in the calculation time, thus reducing the calculation efficiency of finite element analysis. At the same time,

when the pack is subjected to bottom impact, these components are almost never subjected to loads, which is useless for this work. Therefore, they should be deleted before meshing to ensure the accuracy. The focus of attention in this work is on the bottom cover of the battery pack, so the battery module is also simplified. Hyper Mesh is a finite element pre-processing software developed by Altair, with powerful finite element pre-processing functions. In this work, the simplified battery pack CAD model was imported into Hyper Mesh for pre-processing. The small geometric features on the battery pack model are simplified. At the same time, after the battery pack CAD model is imported into Hyper Mesh, there may be some geometric information errors or losses, such as gaps, overlaps and misaligned boundaries on the surfaces, which may prevent normal meshing of the model. Therefore, it is necessary to fill and repair these overlaps, gaps and missing surfaces. The geometrical clean-up of the battery pack can be done in two ways: topology repair and topology optimisation, which are described as follows:

- (1) Extraction of the centre surface of all components except battery packs;
- (2) Removal of fine fillets as well as excess hardpoints created;
- (3) Stitching of free edges and missing surfaces;
- (4) Filling of holes less than 3 mm (Minimum bolt holes in the model are greater than 3mm) in diameter and addition of a layer of washer outside the boundaries of the bolt holes;
- (5) Merge geometric feature lines that are close together or hide them with the toggle command (The distance between the two antennas should be less than 1mm).

4.1.3 Meshing and Quality Optimisation

Mesh delineation can be done by both direct and indirect methods. The direct method is to build the nodes and cells of the model directly in the finite element pre-processing software according to the geometrical shape of the structure. However, this method is only applicable to simple structures or structural systems with special requirements. As for the indirect method, it is to import the 3D model into the finite element pre-processing software first, and then build the finite element model through the geometrical features of the structure such as points, lines, surfaces, etc. It is generally applicable to structural systems with complex geometrical features. Therefore, the indirect method should be used to establish the finite element mesh model of the battery pack. The first step to establish the finite element model should be to select the cell type, and the principles of selection include the shape of the model, the choice of loading calculation method, calculation accuracy and efficiency, etc. Generally, thin-walled structures are simulated by shell cells, and solid structures are simulated by solid cells. Thin-walled structures include: top shell, internal bracket, lifting ear, mounting brackets, trays and bottom shell. They all use shell cells to mesh. The solid structure of the power pack includes the battery module, which is meshed with solid cells. There are two types of shell cells in engineering when drawing the mesh by using shell cells: Hughes-Liu shell cell and Belytschko-Tsay shell cell (Prabowo et al., 2023). Hughes-Liu shell cell is mainly used to deal with the simulation analysis of large deformations, rotations and displacements, and it is a four-node, quadrilateral, thin-shelled cell, which has the disadvantage of lower computational

efficiency and longer time. The simulation time of Hughes-Liu is twice as long as that of Belytschko-Tsay. Belytschko-Tsay shell cell adopts in-plane single-point integration, which is based on the classical theory of thin shells, and it is a kind of thin-shell cell used to deal with the dynamics of the display in a highly efficient way, but the disadvantage is that it lacks of accuracy in dealing with the warping problem. Therefore, considering the calculation time and accuracy, the Belytschko-Tsay shell cell is used to simulate the thin-walled structure in this work. The solid structure is simulated by an eight-node hexahedral solid cell. The selection of the mesh size is also important, and the principle of the size selection is to select the largest mesh possible under the premise of guaranteeing the accuracy of the simulation results, so as to improve the overall computational efficiency (Choudhary and Agarwal, 2023). However, it is not desirable to have too large a mesh, as this will not guarantee the accuracy of the results.

In this work, workstations with 48 cores and 96 threads are used to calculate. 8mm is chosen as the mesh size for the top shell and bottom shell, and 4mm for the internal bracket, lifting ear, mounting brackets, trays. The minimum size of the mesh is limited to 2 mm and the maximum size to 15 mm, and triangular shell mesh can be used for the transition of complex surface geometries. In addition, in the process of meshing, It is also necessary to check the quality of the finite element in terms of aspect ratio, internal angles, warpage and Jacobian to ensure the simulation accuracy of the battery pack mesh model. Considering the calculation capacity of workstations, the criterials are shown in Table 4-1.

Table 4-1. Mesh quality parameter criteria

Parameter	Standard	Parameter	Standard
Warp	$< 7^\circ$	twist	$< 7^\circ$
Aspect Ratio	≤ 5	Jacobian	≤ 0.6
Minimum interior angle of quadrilateral	$> 40^\circ$	Maximum interior angle of quadrilateral	$< 140^\circ$
Minimum internal angle of triangular	$> 30^\circ$	Maximum internal angle of triangular	$< 120^\circ$

After mesh division and optimisation, the final finite element mesh model of the power pack is shown in Figure 4-3. The number of element is 640454, the number of solid elemeny is 127920, the number of nodes is 632653.

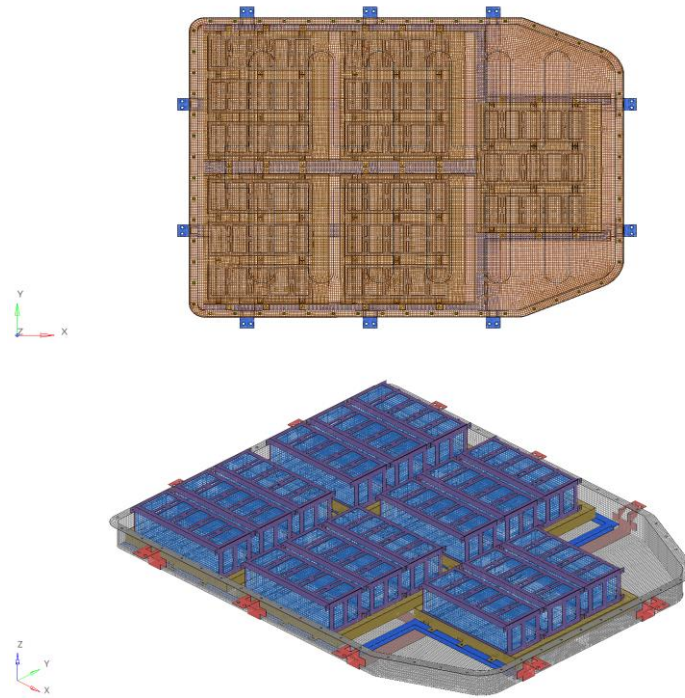


Figure 4-3: Power battery pack FE model

4.1.4 Boundary Condition

The setting of boundary conditions is a necessary step in finite element modelling, which can effectively and accurately simulate the constraints and connection states between parts under different working conditions, so that the simulation results can be closer to the actual situation. In the power battery pack, there are mainly two kinds of connections: weld and bolt. The lifting ear and internal bracket are connected to the bottom shell by welding. The top shell is connected to bottom shell by bolts. All of mounting bracket, trays and internal bracket are connected by bolts. The bolted and welded joints are simulated in HyperMesh software using rigid cells. The connections are shown in Figure 4-4.

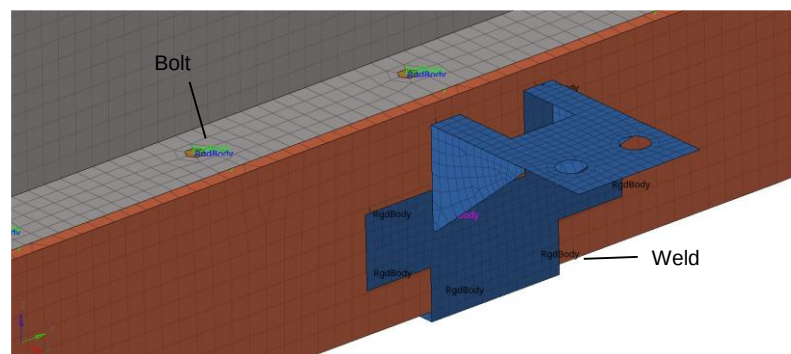


Figure 4-4: Connection simulation diagram

In addition, in order to ensure the computational efficiency of the finite element analysis and simplify the model, all the degrees of freedom of the lifting ear can be constrained to accurately simulate the connection between the battery pack and the body of the EV. The simulation diagram is shown in Figure 4-5.

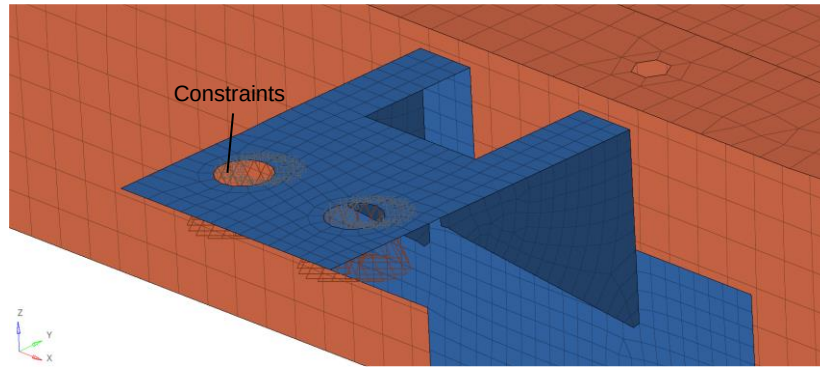


Figure 4-5: Constraint simulation diagram

4.2 Analysis of Model

The validation of the model for the finite element analysis is necessary to ensure the reliability and the effectiveness of the numerical results (H. Wang et al., 2024). According to the type of structural constraints, modal analysis is divided into free and constrained modal analysis. The reason for this is that changes in the boundary conditions directly lead to changes in the frequency and shape of the object. Free modes mean that all parts of the object are not subject to any directional constraints during the modal analysis, and the vibration characteristics of the object are presented as much as possible. On the other hand, the constrained modes are those where the object is constrained in one direction or in different directions. In the case of power packs, they are bolted to the chassis of an electric vehicle and vibrate with the bumps of the vehicle. Therefore, in this work, the constrained modal analysis is used to study the specific vibration pattern and the intrinsic frequency of the battery pack.

4.2.1 Setting

In HyperMesh software, the material models under different types of solvers are different, and the settings of material model parameters are also different. In this work, Optistruct solver developed by Altair, USA is used for modal analysis. MAT1 is chosen as the material model for the top shell, bottom shell, lifting ear and internal bracket. In order to reduce the computation time and improve the computation efficiency, the equivalent mass points of the battery module and other components are converted by using conm2 unit, and the mass is equally divided in the box by using rbe3 unit. In addition, the HyperMesh software does not specify the material properties of the physical units. Therefore, s-mm-ton-ton/mm³-N-Mpa is adopted as the standard physical unit for the finite element model of the battery pack. According to the vehicle manufacturer, advanced high-strength steel and aluminium are used for the structural components of the battery pack. Table 4-2 lists the materials and properties of the main components.

Table 4-2. Material properties of components

Component	Material	Elastic modulus(Mpa)	Poisson's ratio	Density (ton/mm ³)	Yield strength(MPa)
Top shell	6061	7.1×10^4	0.33	2.85×10^{-9}	280

Lifting ear	DP780	2.1×10^5	0.3	7.85×10^{-9}	560
Bottom shell	6061	7.1×10^4	0.33	2.85×10^{-9}	280
Internal bracket	DP780	2.1×10^5	0.3	7.85×10^{-9}	560

4.2.2 Result

In HyperMesh software, the modal analysis method is set to EIGRL, and the frequency range is set to 0-500 Hz. After that, the mesh model of the battery pack is imported into Optistruct for solving. The results of the modal analysis are shown in Table 4-3 and Figure 4-6.

Table 4-3. Modal frequency.

Number of order	Frequency of vibration(Hz)
1	35.68
2	38.55
3	68.24
4	69.96
5	86.71
6	103.91

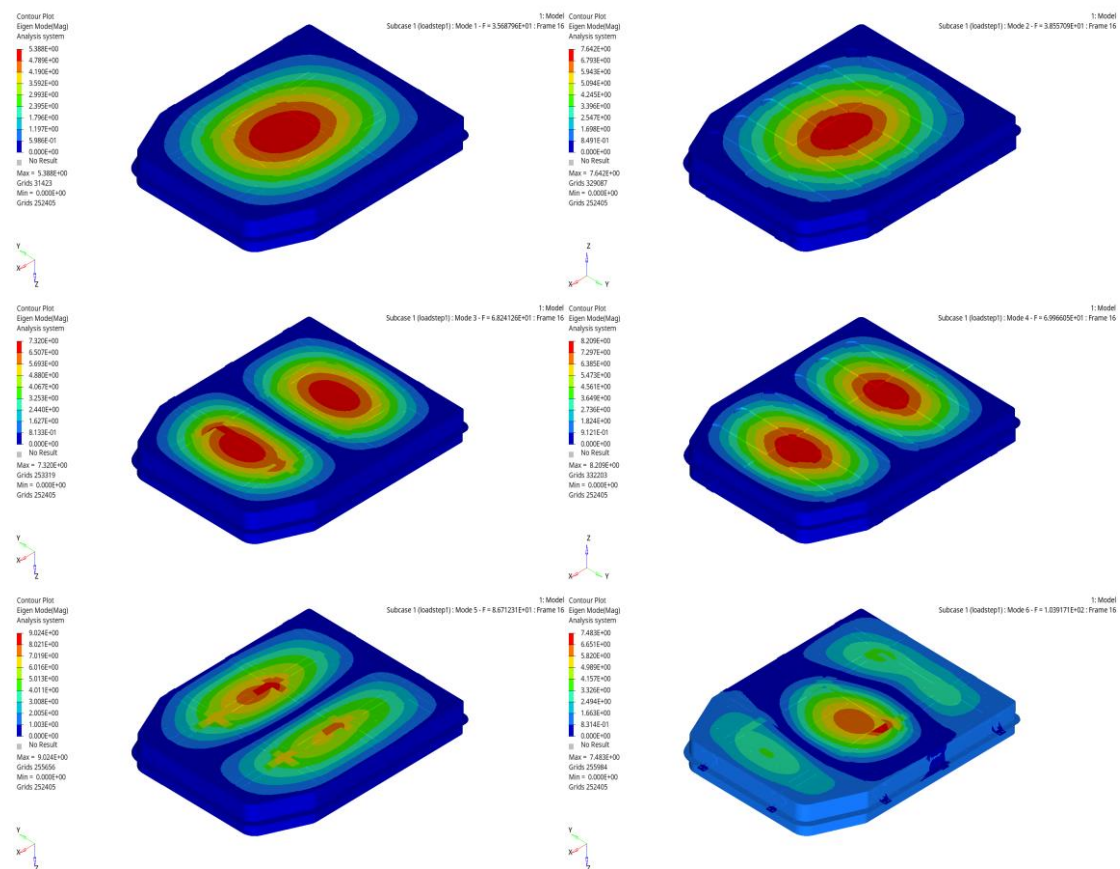


Figure 4-6: Constrained mode shape diagram

The excitation of electric vehicles is mainly caused by the up and down vibration of the wheels when the vehicle is travelling on uneven road surface, and the excitation frequency and vibration pattern of the vehicle are different under different road conditions. When an electric vehicle is driven on a flat road at a speed higher than 100km/h, the excitation frequency of the electric vehicle is generally within 21Hz. The excitation frequency of EVs on various road surfaces ranges from 5 to 30Hz. The first-order vibration frequency of the battery system should be higher than 30 Hz according to the standard (H. Wang et al., 2024). In order to avoid the resonance phenomenon, the intrinsic frequency of the battery pack in each mode should be higher than the excitation frequency of the EV driving on uneven road surface. From the above modal analysis results, it can be seen that the modal frequencies of the battery pack are all higher than 30 Hz, and the first-order vibration frequency is 18% higher than the standard requirement. Thus, the reliability and accuracy of the finite element model of the battery pack are verified.

4.3 Analysis of Bottom Collision

4.3.1 Setting

As mentioned in Section 4.2.1, the material models are different for different solvers. We use LS-DYNA for the finite element simulation of the bottom collision of the battery pack. The MAT24 elastic-plastic material model was chosen for the components of battery back. The obstacle is modelled using the cone model mentioned in Section 3.4. Set $R=10$, $H=80$, $\beta=45^\circ$ according to the point-face contact in section 3.3. Tetrahedral solid cells are used to mesh the obstacle with a mesh size of 4 mm. The obstacle material property is set to MAT_RIGID. The mass is 20kg. The obstacle model is shown in Figure 4-7.

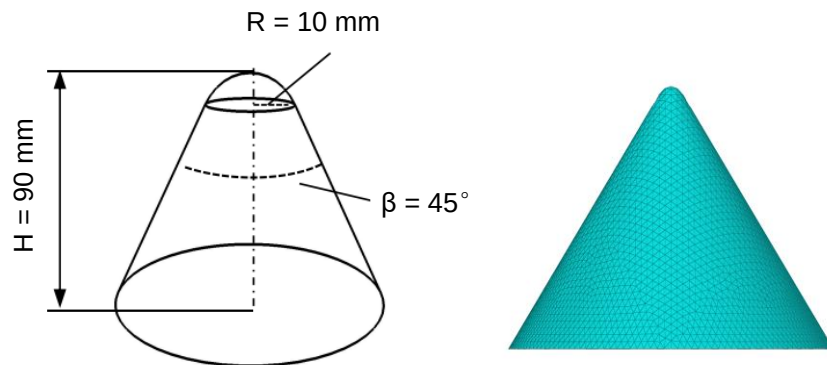


Figure 4-7: Obstacle model

The initial velocity of the obstacle is set to be $v=10\text{m/s}$. Based on the reality, the point of collision between the obstacle and the bottom of the battery pack is random when the obstacle is on the road. Therefore, the location of the obstacle is set to the middle area of the bottom of the battery pack, avoiding the bracket area, as shown in Figure 4-8. In order to be the worst case The contact type between the obstacle and the bottom surface of the battery pack is set as

'CONTACT_AUTOMATIC_SURFACE_TO_SURFACE', and the contact type of the internal components of the battery pack is set as 'CONTACT_AUTOMATIC_SINGLE_SURFACE'. The coefficient of friction between the members is automatically set to 0.5. Considering the configuration of workstations, the simulation time is 0.1s, the calculation step is 8.1e-6s, and the time interval of the animation output is 0.005s.

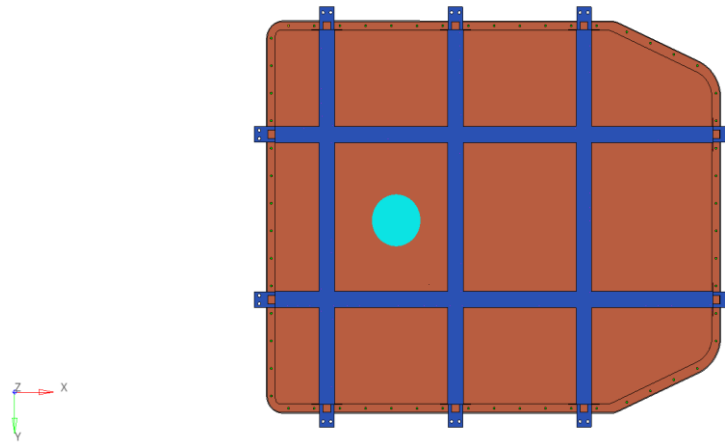


Figure 4-8: Obstacle location

4.3.2 Result

4.3.2.1 Model Validation

After setting the calculation parameters, the K-file is exported and LS-DYNA is used to solve the calculation. In order to verify the credibility of the calculation, the energy changes during the collision simulation are analysed, as shown in Figure 4-9. The total energy of the system tends to be stable and unchanged, with the internal energy increasing and the kinetic energy decreasing, and it tends to be stable around 80ms. Hourglass energy less than 5% of the total energy is acceptable. Now, the hourglass energy is very small in the collision of foreign objects on the road. It meets the calculation requirements of simulation. The comprehensive analysis shows the accuracy of the finite element model of the bottom collision between the power pack and the obstacle.

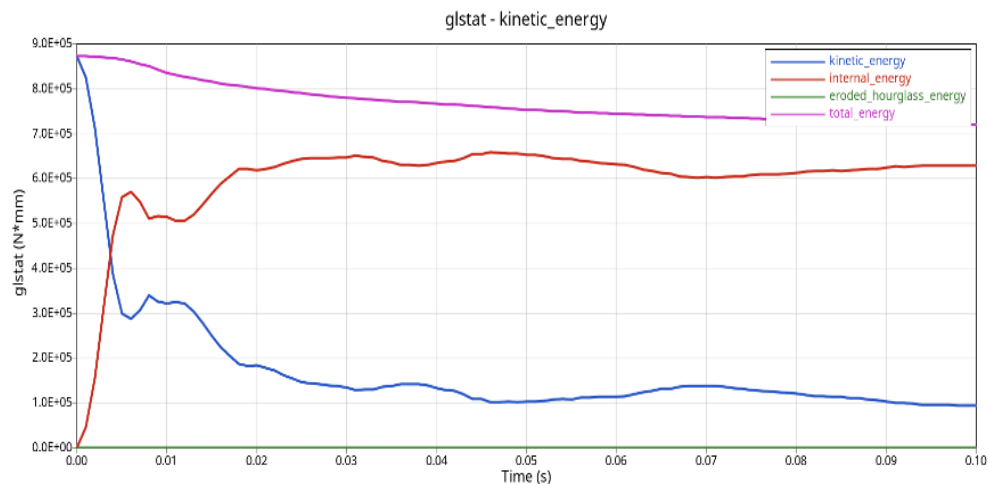


Figure 4-9: Energy change during collision

4.3.2.2 Process of Deformation

During the collision between the bottom of the battery pack and the obstacle, the bottom of the battery pack box is squeezed vertically upwards, and the deformation of the box will affect the safety of the internal electrical components and battery modules. Figure 4-10 shows the displacement of the battery pack under the obstacle impact (10ms interval). Combined with Figure 4-9, it can be seen that the obstacle moves upward along the Z-axis with an initial velocity of 10m/s. In 0-10ms, the obstacle and the battery pack start to contact, the obstacle is hindered by the battery pack, the kinetic energy decreases rapidly, the internal energy of the battery pack increases, and the battery pack is deformed. Subsequently, the rigid obstacle further squeezes the bottom of the battery pack, and the deformation of the box further intensifies, resulting in the deformation of the internal components of the battery pack. The period of 20-80ms is the post-crash phase. A large area of the lower cover of the battery pack was deformed. Eventually, after 80ms, the system energy stabilises. From the deformation process of 0-100ms battery pack case bottom collision with obstacles, it shows that the battery pack lower cover has poor stiffness, weak collision resistance, and poor energy absorption, which may cause secondary damage to the internal parts of the battery pack. As stated in section 2.2.3, this mechanical abuse will lead to short-circuiting of the battery and can even lead to thermal runaway and fire. Therefore, it is necessary to improve the stiffness of the battery pack lower cover, reduce its deformation, and improve the overall safety of the battery pack.

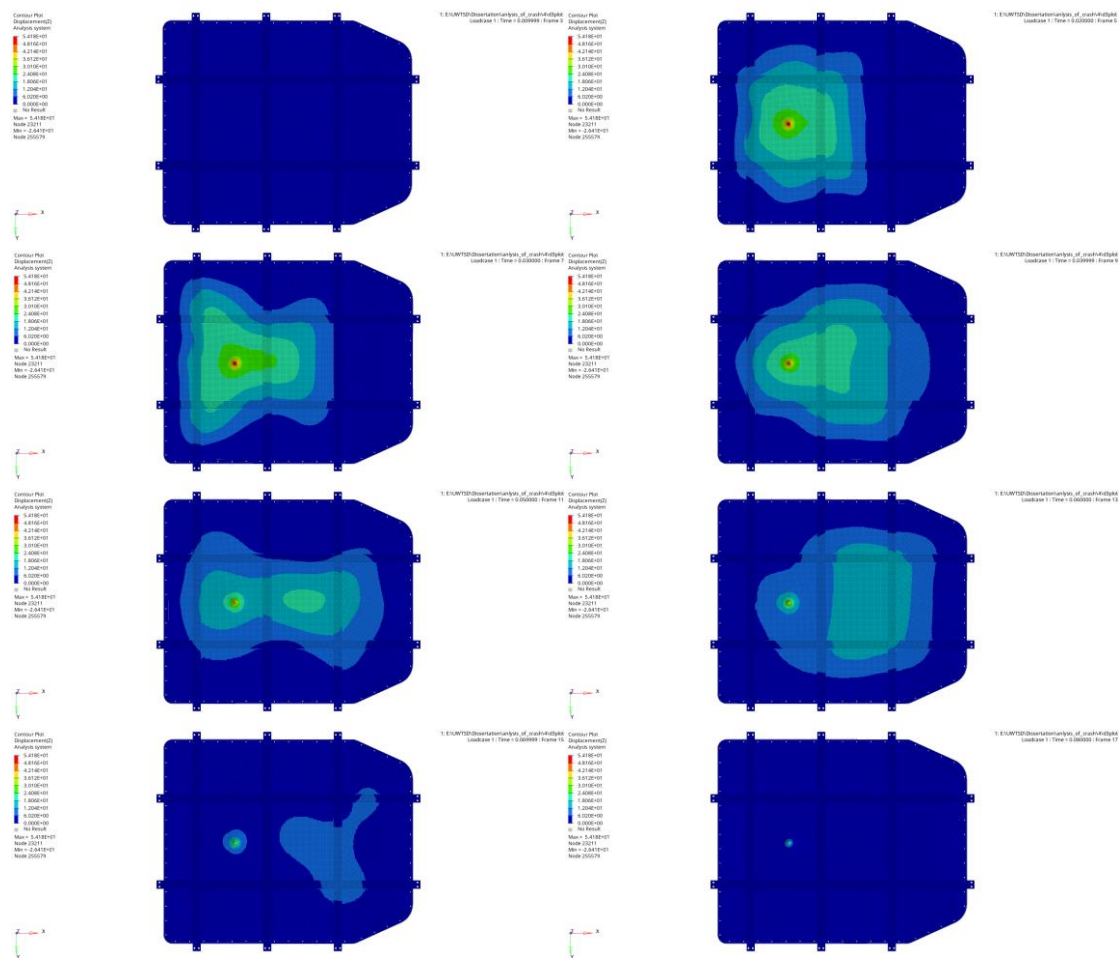


Figure 4-10: Battery pack bottom shell displacement

4.3.2.3 Damage Analysis

In the process of collision between the bottom of the battery pack and the obstacle, the lower cover is the first to be contacted, and with the continuous upward movement of the obstacle, other parts inside the battery pack are extruded and deformed accordingly. The damage analysis of the battery pack is carried out on the bottom shell, lifting ear and internal bracket.

(1) bottom shell and lifting ear

The main function of the bottom shell of the battery pack is to contain and protect the internal electrical components and battery modules, and the degree of damage to it affects the safety of the internal electrical components and battery modules. Lifting ear, as the key connection between the EV body and the battery pack, the degree of damage determines whether the battery pack is fixed to the vehicle body in its original state. The material of the bottom shell is 6061T6 aluminium alloy with a yield strength of 280 MPa and a tensile strength of 310-350 MPa, and the material of the lifting ear is DP780 steel with a yield strength of 560 MPa and a tensile strength of 780-800 MPa. Figure 4-11 shows the stress distribution of the bottom shell and the lifting ear in the process of the collision. As can be seen from the figure, the maximum stress of the bottom shell occurs at the impact point and its surrounding area, and the maximum stress is 300 MPa. Its

stress value is obviously larger than the yield strength, and it will produce obvious plastic deformation. The maximum stress of the lifting ear appears in the red circle area and the lifting ear in the upper left corner of the figure, with a maximum value of 780 MPa. Its stress value reaches the tensile strength, and under the impact of the obstacle, the battery pack lifting ear has a high possibility of rupture and failure.

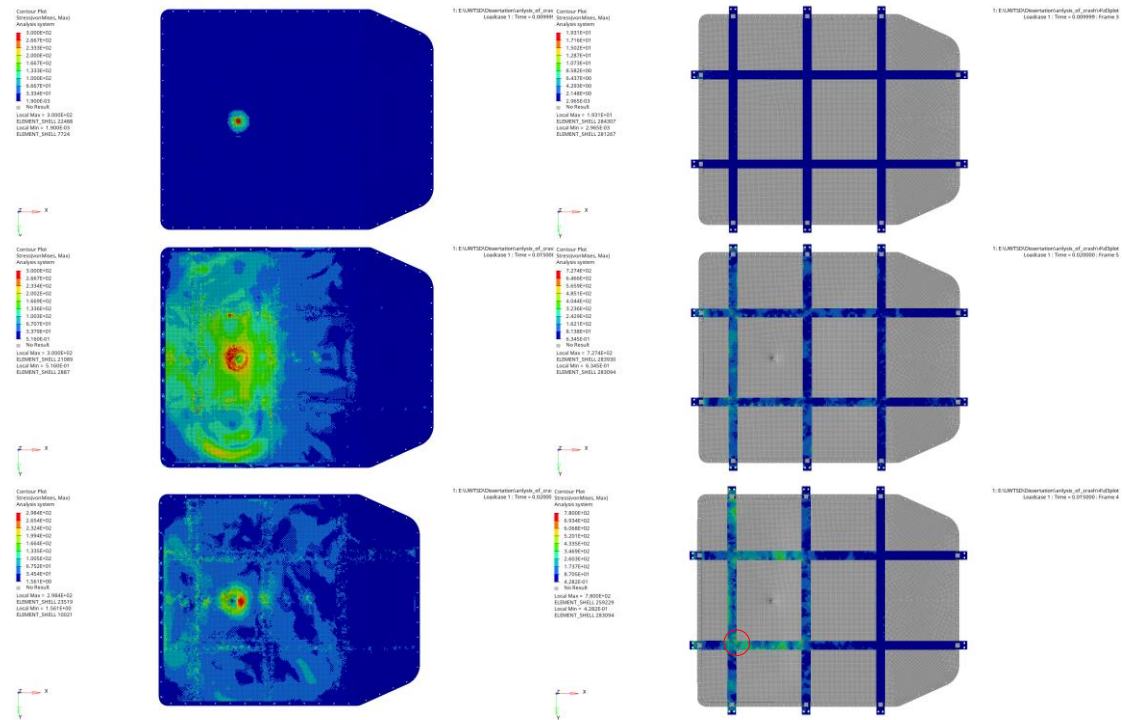


Figure 4-11: Stress distribution diagram of bottom shell and lifting ear

(2) Internal Bracket

The material of the internal bracket is steel, and the deformation stress diagram is shown in Figure 4-12. During the collision process, the internal bracket has a tendency to move upwards, and the distribution area of the maximum stress value of the plastic frame is mainly in the area directly above the collision area of the obstacle. The maximum stress value is 780MPa. There is a risk of fracture in this area.

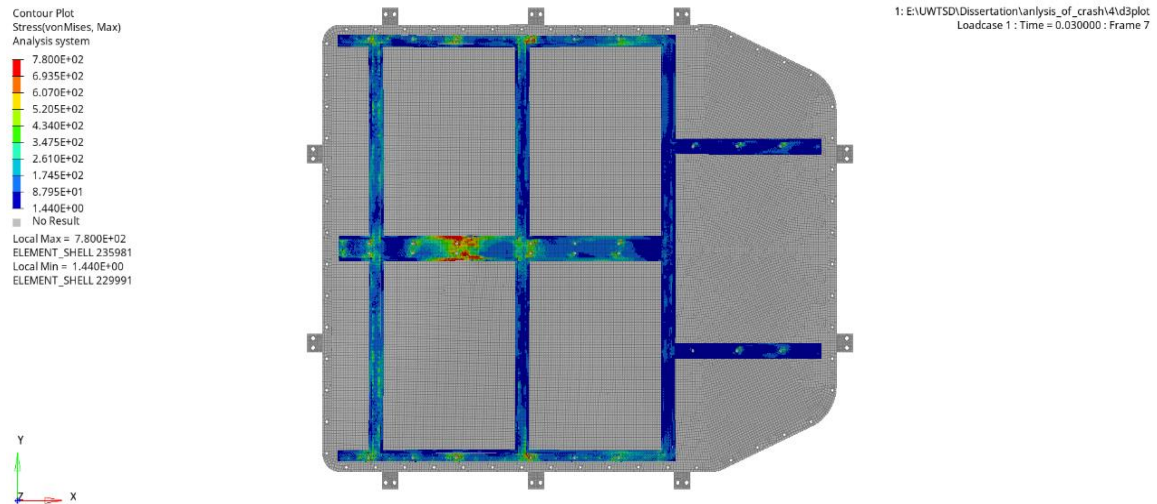


Figure 4-12: Internal bracket stress distribution

(3) Trays

The tray is made of aluminium alloy, and its stress diagram is shown in Figure 4-13, during the collision process, the tray has an upward movement tendency, and the maximum stress value distribution area is mainly in the collision area, the maximum stress value is 280MPa, and yield deformation begins to occur. The tray and internal bracket connection area has obvious plastic deformation, this is due to the deformation of the bottom shell after cash with obstacle. The maximum stress value exceeds the yield limit, there is a risk of rupture at the fixed place.

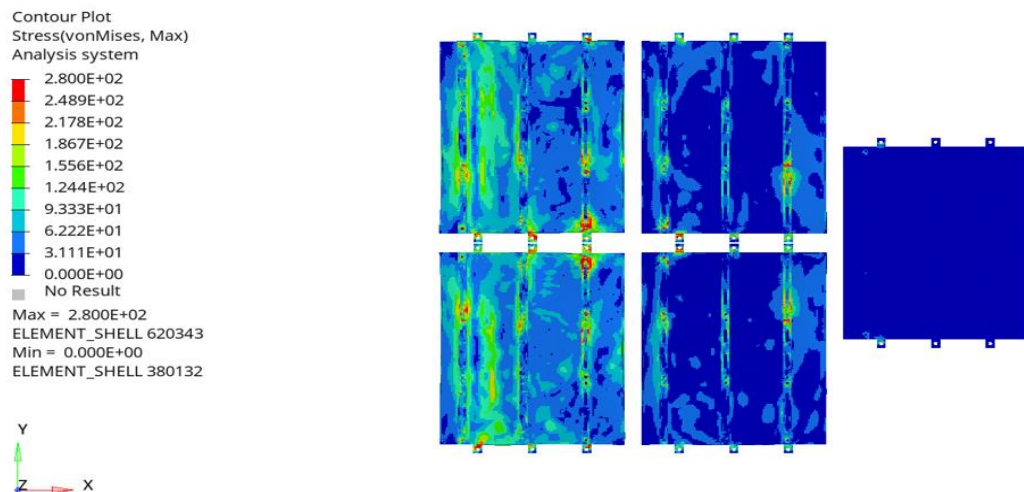


Figure 4-13: Stress map of trays

(4) Mounting bracket

Figure 4-14 shows the stress distribution of the mounting brackets. The area with the maximum stress value is mainly at the top corner of the bracket. The maximum stress value is 280MPa, and the internal structure is not seriously deformed, which should be due to the deformation of the bottom of the battery box extrusion and the inertia of the battery module, in the vertical direction (Z-direction) of the larger displacement, should be strengthened inside the pack vertical fixation effect.

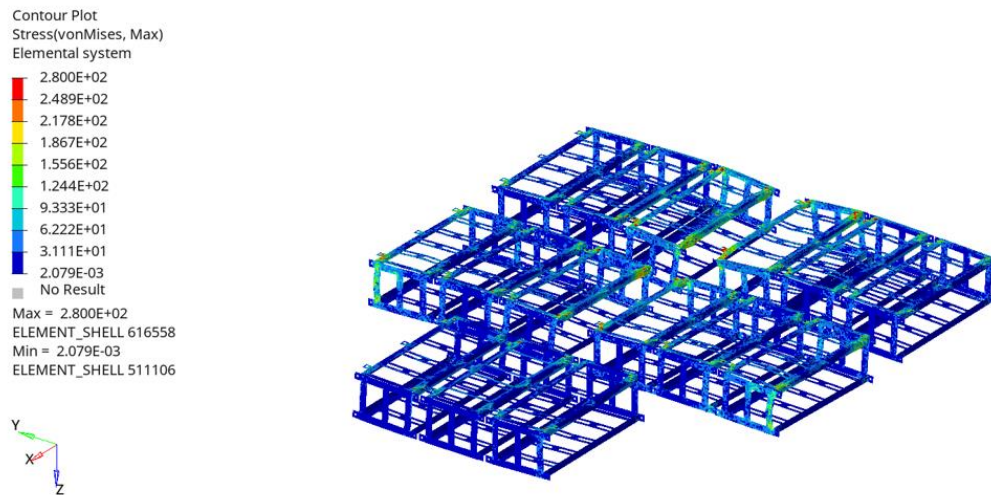


Figure 4-14: Stress map of mounting bracket

(5) Battery module

Figure 4-15 shows the stress distribution of the battery modules. The middle four modules are closest to the impact site. The vertical deformation of the bottom shell produces a large compression force on the internal components directly above it, so the battery modules close to the impact site are most affected by the damage. The top of the module produces stress concentration, the maximum stress is 51MPa. This is much lower than the failure stress value of the cylindrical battery shell (aluminium). At this time, the overall stress on the battery module is uniform, the deformation of the battery is small, and the battery will not be short-circuited internally, but the movement of the battery module in the vertical direction (Z-direction) is large, which may lead to the failure of the electrical connection between the modules. Therefore, it is necessary to improve the vertical fixation ability of the battery module to reduce the risk of electrical connection failure under the condition of impact between the chassis and obstacles.

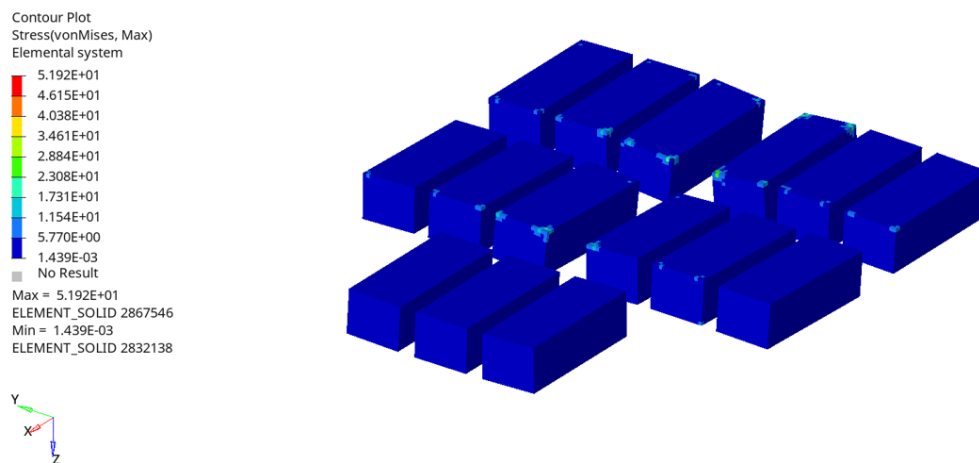


Figure 4-15: Stress of module at the end moment

5 Influence of Material and Thickness

Faced with the problems of environmental pollution and the high cost of aluminium chassis mentioned in section 1, the application of UHSS may be a good option. In fact, steel components have the lowest CO₂ emissions compared to alternative materials such as aluminium. For a body-in-white, an automotive component made from AHSS steel emits less than half the CO₂ of an equivalent aluminium component, and less than one-third of the emissions of a carbon fibre reinforced plastic component. In addition, steel is 100% recyclable, and because of its Life Cycle Analysis (LCA) benefits, steel remains an important material in a sustainable circular economy. (“GONVVAMA in news”, 2021.). Therefore, DP780 was used as the material for the bottom shell and DP980 as the material for the lugs and internal supports, and orthogonal tests were designed to determine the thickness of the components.

5.1.1 Test Programme

The test factors were the bottom shell, lifting ear, and internal bracket, labelled as A and B respectively, and each factor corresponded to two different levels. In this test, three factors and two levels of orthogonal tests were carried out. According to the result of (Pan et al., 2022), the specific test parameters are given in Table 5-1.

Table 5-1. Experimental parameters

unit:mm

Level	Factor	
	A	B
1	1.6	1.8
2	1.8	2

5.1.2 Result

The levels of each factor of the experimental design were filled in the orthogonal test table and finite element calculations were performed for different scenarios. Select a node at the bottom of the finite element model of the battery pack, set the NODOUT control card and OUT_BOLCK,output its displacement. The displacement of the same node at different thicknesses is shown in Figure 5-1. The results are shown in Table 5-2.

Table 5-2. Result of test

Order	A	B	Mass/kg	Displacement/mm
1	1.6	1.8	412	38.47
2	1.6	2	411	37.95
3	1.8	1.8	415	36.88
4	1.8	2	417	35.88

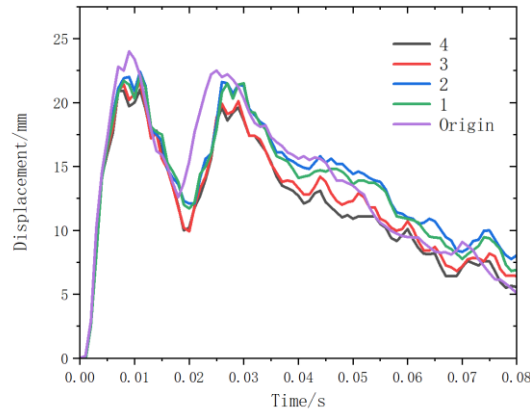


Figure 5-1: Nodal displacement

From the final experimental data we can conclude that the displacement of the nodes under the fourth option is minimal. At the same time there is no increase in mass compared to the initial model. Initially the mass of the battery pack was 419kg. The maximum displacement of the fourth scenario was reduced by 9 % compared to the original model.

The effective plastic deformation of the bottom shell before and after optimisation is analysed and the results are shown in Figure 5-2. Before optimisation. The maximum value of the bottom shell of the battery pack is 0.46. After optimisation the maximum value is 0.38. The effective plastic deformation is reduced by 17.14%.

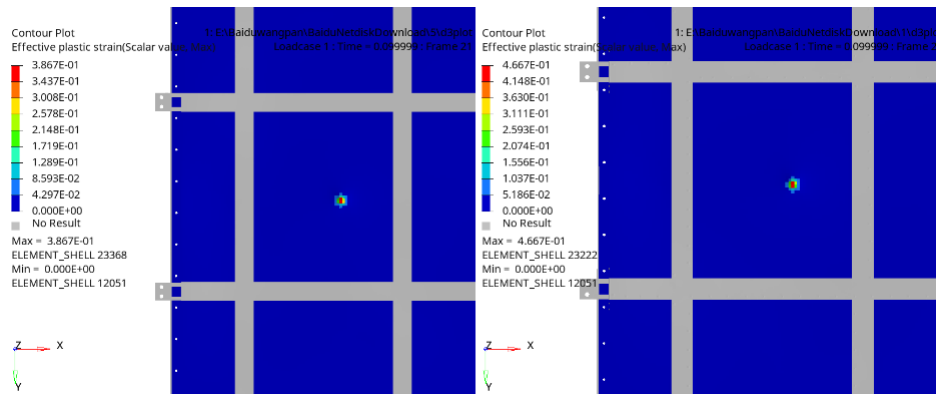


Figure 5-2: Effective plastic strain of bottom

6 Ongoing work

This section of the report pertains to the future and ongoing efforts in developing the project.

1. Although a conic model was used to parametrically model the obstacles in chapter 3, it does not provide a comprehensive picture of the geometric characteristics of the different obstacles. The dynamics of the collision between the obstacle and the underside of the car also needs to be analysed.

2. Although a modal analysis of the finite element model of the battery pack was carried out in Chapter 4 and the results showed that its vibration frequency meets the practical requirements, a physical model should be established to measure the frequency of the battery pack in real situations to further verify the correctness of the model.
3. When establishing the finite element model of the battery pack, the battery module should be modelled in a more detailed way to further study the response of the internal parts of the battery pack when it receives a bottom collision.
4. During this analysis that all the connections were seemed to be infinitely rigid, it's recommended that the this study is carried out with deformable joints.
5. The study of the material and thickness of the bottom shell of the battery pack can be extended to include other materials such as composites, carbon fibre etc.
6. Optimisation of the battery pack chassis can be investigated in more depth, e.g. by applying neural networks to find the best material and related parameters.
7. All results should ultimately be analysed and verified in a physical test of the vehicle.

7 Conclusion

In conclusion, in the face of the lack of a large amount of data related to the bottom crash with battery packs, the use of advanced and low-cost numerical analysis has become one of the important ways to improve the safety of power battery packs for electric vehicles. In this work, a parametric model is used to model and simulate the obstacles present on the road. A finite element model of the battery pack is successfully developed and validated for simulating bottom collisions and performing crash damage analysis of the battery pack. The results show that the bottom shell, lifting ear, and internal brackets of the battery pack have plastic deformation, and the battery module has a tendency to move upwards without the risk of fracture failure. The bottom shell of the battery pack plays a crucial role in absorbing the impact energy and protecting the internal components. By optimising the material selection and thickness of the casing, the overall impact resistance of the battery pack can be improved. These results highlight the importance of material innovation and design optimisation in improving the safety of electric vehicles. Future work will focus on further refining the model, exploring alternative materials, and conducting physical tests to validate the simulation results. Insights gained from this study are expected to inform the design of stronger and safer electric vehicles, in line with global efforts to promote sustainable and efficient transport.

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