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Structural improvment of a miniature pure electric vehicle in small overlap front impact

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Abstract: The finite element model of a domestic miniature pure electric vehicle is established by using CAE software. According to the requirements of IIHS evaluation system, 25% overlapping offset collision simulation is carried out. According to the simulation results, the deformation of the car body structure and the intrusion of each measuring point during the collision process are analyzed. Aiming at the existing problems in the structure crashworthiness of the vehicle, structural improvement measures are put forward, including structural improvement and material strengthening. The optimized model is simulated again with 25% small offset collision. The optimized scheme can significantly improve the crashworthiness of the car body structure and greatly reduce the invasion of the passenger compartment. At the same time, full-width frontal impact and 40% offset impact conditions will be validated. By comparing the changes of body deceleration and intrusion volume of main observation points, it can be concluded that the improved body stiffness is reasonable.

Keywords: small overlap front-impact; structural improvement; finite element analysis(FEA); crashworthiness

1 Introduction

According to relevant statistics, frontal collision is the highest proportion of all traffic accidents, and there is a type of frontal collision - small offset collision, which has a high fatality rate, accounting for about 25% of frontal collision deaths[1-2]. According to the AAE statistics, the proportion of small offset collisions is about 24% of all frontal collisions, while the proportion of full width frontal collisions is only 6%. In order to further improve the crashworthiness of vehicle in frontal collision and reduce the loss of personnel and property caused by small offset collision, the American Highway Safety Insurance Association (IIHS) issued a 25% frontal small offset collision test code in 2012, which specifies the method, test speed and scoring criteria of collision test in detail[3-4]. On February 28, 2018, China released the China Insurance Automobile Safety Index System (C-IASI) by China Insurance Research Institute of Automobile Technology and China Automobile Engineering Research Institute, which formally included 25% of the frontal offset impact.

In recent years, with the development of new energy vehicles in China, more and more two miniature pure electric vehicles have appeared in the market. The compact structure, low price, convenience and flexibility of micro pure electric vehicles have attracted more and more attention. However, the configuration of this kind of electric vehicle is relatively simple, the space is relatively narrow, the front cabin energy absorption space is generally insufficient, and some of them are not even equipped with airbags. Once a small offset collision occurs, it is very likely to cause serious occupant casualties. Therefore, the research on 25% offset impact of micro pure electric vehicle is of great significance.

In this paper, LS-DYNA software is used to simulate a 25% small offset collision of a miniature pure electric vehicle. According to the simulation results, the deformation of the car body and the main stress components are observed. According to the scoring standard proposed by IIHS, the car body structure is graded, the existing problems of Crashworthiness of the car body structure are analyzed, and the structural improvement scheme to solve these problems is put forward. By comparing the simulation results before and after improvement, it is proved that the improvement scheme is feasible.

2 IIHS Rules for Crash Test and Evaluation of 25% Small Bias on Driver Side

IIHS The 25% small offset collision test procedure on the driver side stipulates that 50% dummy is placed in the driver's position and that 25% of the body width and rigid barrier contact are guaranteed at the moment of collision between the test vehicle and the barrier. The front end of the rigid barrier is a cylindrical arc with a radius of 150 mm and a radian of 115 rad. The impact velocity of the test vehicle is 64 km/h. The test conditions are shown in Figure 1[5-7]. Collision rating is evaluated from three aspects: restraint system, dummy damage value and car body structure deformation. The structural deformation of the car body is evaluated by the intrusion of 10 monitoring points in the passenger compartment, as shown in Figure 2. These 10 monitoring points are divided into two parts: the upper part of the crew cabin includes the upper part of the dashboard, the left side of the dashboard, the hinge on A-pillar and the steering column; the lower part of the crew cabin includes the threshold beam, the parking pedal, the brake pedal, the left footrest area, the footrest area and the lower hinge. The intrusion volume of the upper and lower parts of the passenger compartment is evaluated separately, and the worse evaluation of the upper and lower parts is taken as the final rating result of the crashworthiness of the structure of the vehicle.

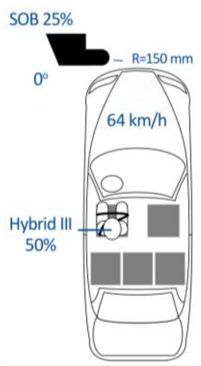


Figure 1. Small offset collision test condition

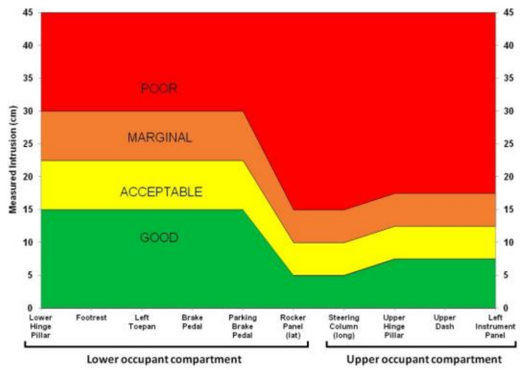


Figure 2. Crew compartment intrusion rating standard

3 Establishment of Finite Element Model

In this paper, a domestic pure electric vehicle is selected to build the whole vehicle model. According to the requirements of IIHS for small offset collision test, the collision model of this condition is established. In order to improve the calculation efficiency, the rigid barrier is simplified. In this paper, the height of the barrier is 1524 mm, the radian is 115 degrees, the radius of the arc is 150 mm, the mesh size is 10 mm, and the material of the barrier is selected by MAT20. The keyword BOUNDARY_SPC is used to restrict the degree of freedom of the barrier, and the contact relationship between the whole vehicle and the barrier is defined by CONTACT_SURFACE_TO_SURFACE. The speed of the whole vehicle at the time of collision is defined as 64km/h. The finite element model is shown in Figure 3. The internal energy, kinetic energy, hourglass energy and total energy of the model are extracted as shown in Figure 4. The total energy of the model is 196.5KJ, of which the hourglass energy is 2.1KJ, accounting for 1.06%. Therefore, the model is believed to be credible.

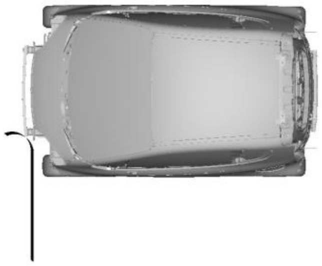


Figure 3. Finite element model

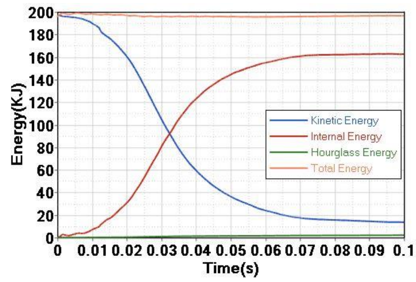
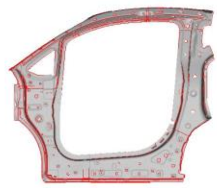
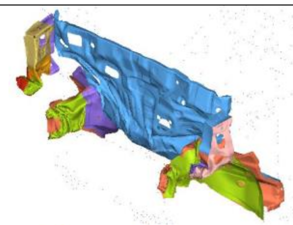
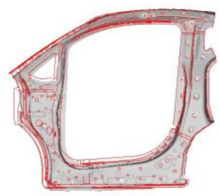
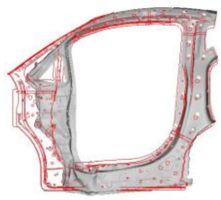
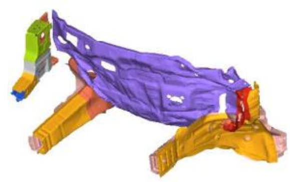


Figure 4. Collision energy curve

4 Analysis of Three Front Collision Conditions

This paper establishes three frontal crash conditions: 100% full width front crash, 40% offset front crash and small offset front crash. The simulation results of three conditions are compared from three main aspects: body deformation, passenger compartment intrusion and force transfer path.

Table 1. Analysis of vehicle collision deformation

Collision condition	Body deformation	Door frame deformation	Longitudinal beam deformation
100% front collision			
40% offset impact			
Small overlap front crash			

4.1 Body Deformation Analysis

The deformation of the vehicle in three frontal crash States is shown in Table 1. Under full frontal crash conditions, the front longitudinal beam, bumper, energy absorbing box, sub-frame and other energy absorbing components all participate in the crash process, and the deformation of the passenger compartment is relatively small. In 40% offset impact, the bumper, energy absorbing box, front longitudinal beam and sub-frame on the left side of the vehicle all participate in the collision process[8-9]. The energy absorbing effect is good, and the deformation of the passenger compartment is small.

Under the condition of small offset collision, the area where the collision occurs is in the front of the body, and this part can not be protected by the collapse deformation of energy absorbing components such as bumper, energy absorbing box and front longitudinal beam. The collision load is transmitted directly through the front wheel, suspension system and front panel, and then enters the passenger compartment backwards, which causes relatively large invasion of the passenger compartment and serious injury to the legs and feet. The barrier first contacts with the body panels, then collides with the upper beams. The collision force is transmitted to the hinge column, and then to the A-pillar, which results in the larger deformation of the A-pillar and increases the deformation of the hinge column. The intrusion of the lower part of the passenger compartment mainly comes from the extrusion of tires. The energy absorbing components in frontal and offset collisions do not play their due role in small offset collisions, which results in a huge impact on the wheels and then squeezes the threshold beams backwards.

4.2 Analysis of Invasion Quantity

According to IIHS, the crashworthiness evaluation of body structure under small offset crash is achieved by measuring the invasion of passenger compartment. According to the requirements, 10 measuring points are selected for the upper and lower parts of the passenger compartment, and they are rated separately. The worse of the two rating points is taken as the final rating for the crashworthiness evaluation of the whole body. When rating the two parts separately, each measuring point falls into different rating areas, and the final rating takes the area where each measuring point appears most frequently[10-11]. As shown in Fig. 5, the deformation of the passenger compartment is the most serious in the small offset collision. The deformation of the passenger compartment in the 100% front and 40% bias offset collisions is relatively small.

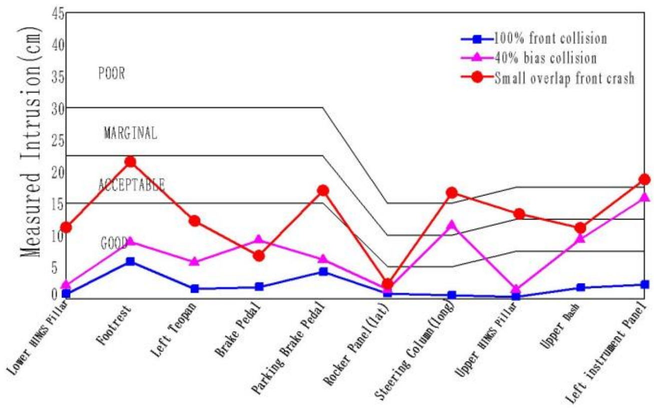


Figure 5. Body structure rating

4.3 Analysis of Force Transfer Path

In 100% full width frontal crash, the whole vehicle is in complete contact with the rigid wall. There are three main force transfer paths: the first path is transmitted back along A-pillar through shotgun; the second path is transmitted back along the floor through bumper beam; the last path is transmitted directly to the threshold through tire, and then from the threshold to the back. The transmission path of frontal collision is equal, as shown in Figure 6.

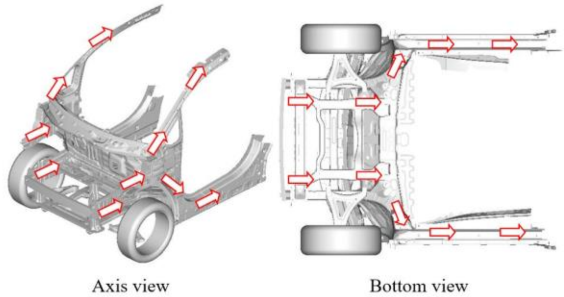


Figure 6. Force transfer path in 100% front collision

In 40% offset collision, the collision force mainly passes through the left side of the vehicle because only part of the body structure has contact with the barrier. The force transfer path passes through bumper, left front longitudinal beam, threshold, shotgun and A-pillar and other components. Because the front force is not uniform, it is easy to deflect the vehicle in the process of collision, leading to the bending and instability of the main energy-absorbing components in the process of collision. The path of force transmission is shown in Fig. 7. In 25% small offset collision, because the front longitudinal beam can not contact the rigid barrier, the front longitudinal beam can not transmit the impact force in the collision. The collision force is transmitted to A-pillar through shotgun and to the threshold through tire. Therefore, compared with the other two collision conditions, the transmission path of small offset collision is the least, and the transmission path is shown in Figure 8.

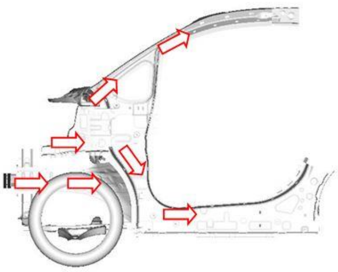


Figure 7. Force transfer path in 40% offset impact

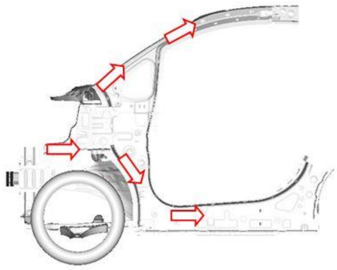


Figure 8. Force transfer path in small overlap front collision

5 Structural Improvement Based on Small Offset Collision

Aiming at the deformation characteristics of the vehicle in small offset collision, the force transfer path of the vehicle is reasonably arranged, the shape and thickness of key parts are optimized, the stiffness of the passenger compartment is improved, and the invasion of the passenger compartment caused by the collision is reduced.

5.1 Structural Improvement of Forebay

Referring to the structure of Honda ACE and Toyota TNGA, as shown in Fig. 9 and Fig. 10, shotgun and crossbeam are connected with connectors to form a closed ring structure with guiding effect[12-13]. Both the front longitudinal beam and shotgun are independent load transfer paths. They do not form a ring structure with closed paths, resulting in a cantilever structure. Without considering whether the technology can be realized, shotgun is extended to the front end of the front longitudinal beam, the extension part is connected by solder joints, and the extended shotgun is guaranteed not to affect the movement space of the wheels. The optimized shotgun is compared with the one shown in Fig. 11 and Fig. 12.

Figure 9. Honda ACE structure

Figure 10. Toyota TNGA structure

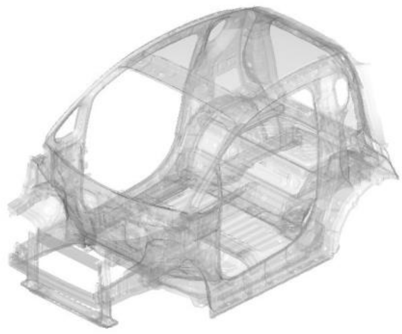


Figure 11. Before structural optimization

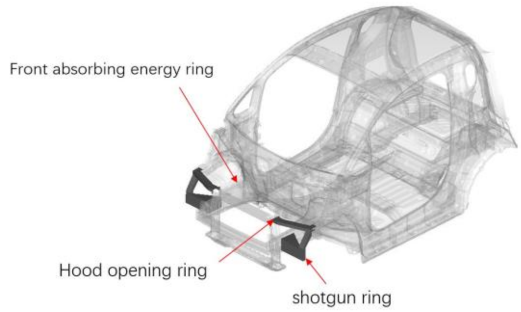
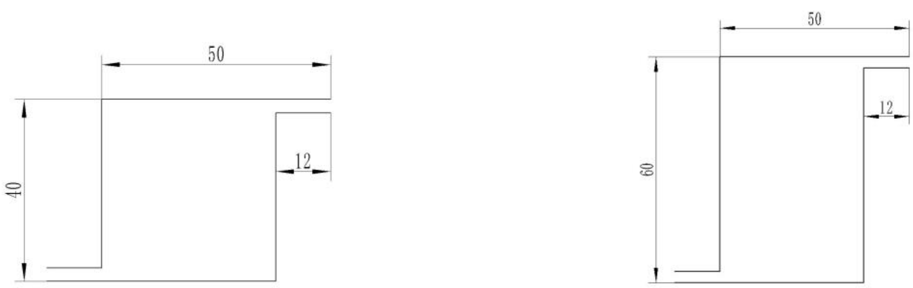


Figure 12. After structural improvement

There is only one load transfer path at the front end of the car body, so the cross-section size of the upper beam should be enlarged to increase its energy absorption efficiency. Inelastic Instability Strength of Thin-walled Beams with Square Section $\sigma_{cr} = \frac{\pi^2 E_S}{9}(\frac{t}{b})^2 \left[\left(\frac{1}{4} + \frac{3}{4}\frac{E_1}{E_2} \right) \left(\frac{mb}{L} \right)^2 + 2 + \left(\frac{L}{mb} \right)^2 \right]$ [13-14], Es and E1 are the elastic modulus and material strengthening modulus of thin-walled beam with square cross-section, t is the thickness of beam, B is the width of cross-section, m is half wave number, L is the length of cross-section. Therefore, it is preferable to lengthen the section height of the upper beam. Fig. 13 is the cross-section size comparison of the upper girder structure before and after improvement. The improved upper girder is obtained by downward stretching 20 mm from the upper girder on the premise of keeping part of the size unchanged.



（a） Before improvement **（b） After structural improvement**

Figure 13. Comparison of upper Side Beam Section Size before and after Optimizing

Increase the transverse transmission channel and increase the cross beam in front of the front panel[15-16]. The collision force is transferred to the rear and non-collision side of the car body to ensure the smooth transmission path. The scheme is shown in Figure 14.

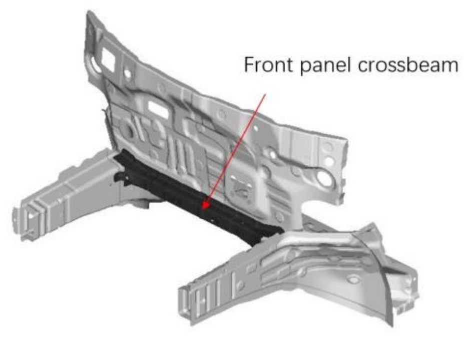


Figure 14. Diagram of front panel crossbeam

5.2 Increased Strength of Crew Compartment

Increasing the energy absorption of the front-end structure and optimizing the force path put forward higher requirements for the carrying capacity of the passenger compartment. Increasing the strength of the passenger compartment will help to better resist deformation, so material strengthening is considered. Thermoforming steel has been used in the threshold beam, A-pillar and hinge column of the car. Therefore, it is considered to increase the thickness of the key parts to enhance the strength of the cabin. The schematic diagram of the position of the thickened components is shown in Fig. 15, and the material and thickness changes of the main optimized components are shown in Table 2.

Table 2. Major optimized component material and thickness change

optimized component	material	original thickness	improved thickness
Shotgun ring	HC340/590DP		1.4
Hood opening ring	HC340/590DP		1.4
Upper side beam	HC340/590DP	1.2	1.4
Front panel cross beam	HC340/590DP		1.4
Threshold beam	B1500HS	1.2	1.4
A-pillar	B1500HS	1.2	1.4
Hinge pillar	B1500HS	1.2	1.4

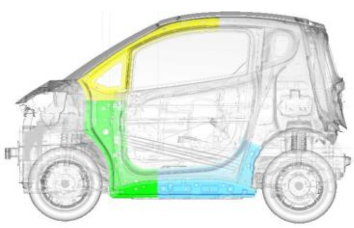


Figure 15. Schematic diagram of crew compartment component thickening

5.3 Analysis of Improvement Results of Small Offset Collision

The optimized vehicle model is simulated again with small offset collision, and the results are evaluated. After improvement, the invasion of crew cabin is shown in Fig. 16, and the invasion of crew cabin has been greatly improved. Therefore, the improvement scheme is helpful to improve the structural crashworthiness of the vehicle in small offset collision[17-18].

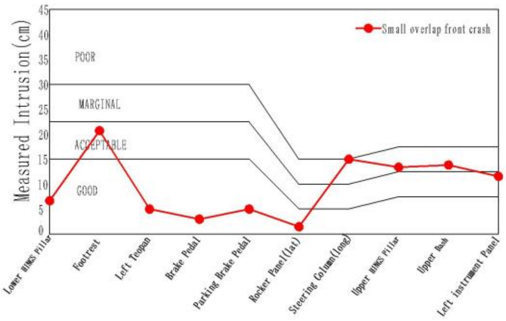


Figure 16. Rating of optimized body structure

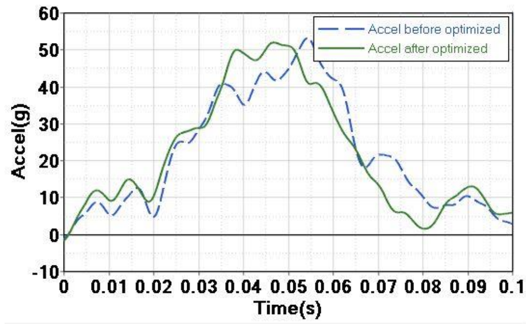
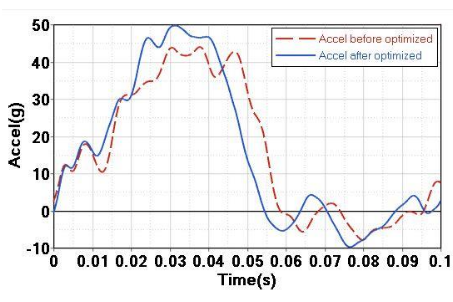


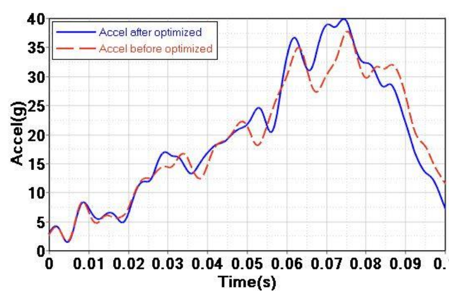
Figure 17. Acceleration contrast on vehicle body under small offset impact before and after Optimizing

After structural improvement, the acceleration comparison of the car body is shown in Figure 17. After improvement, the acceleration between 30ms and 60ms is increased and the peak acceleration is reached ahead of schedule, which is due to the earlier time of shotgun participation in the collision at the front of the car body. Due to the increase of energy absorption at the front end of the car body and the decrease of the tire extrusion threshold in Chengdu, the peak acceleration of the car body is lower than that before improvement.

5.4 Compatibility Verification of Optimized Scheme

As the stiffness of the front cabin increases, it is necessary to re-verify the full-width frontal impact and 40% offset impact, and verify whether the improvement scheme meets the body safety requirements by comparing the body acceleration and the front panel intrusion. The comparison of body acceleration between front and offset crashes before and after improvement is shown in Fig. 18, and the peak acceleration of both conditions increases.

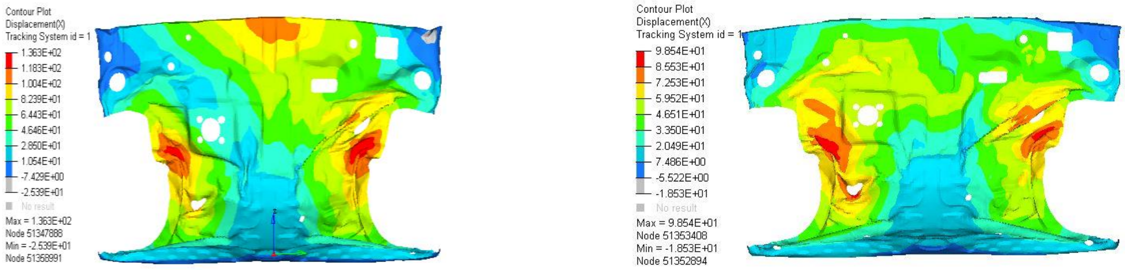




（a） **Body Acceleration in 100% front collision** （b） **Body Acceleration in 40% offset impact**

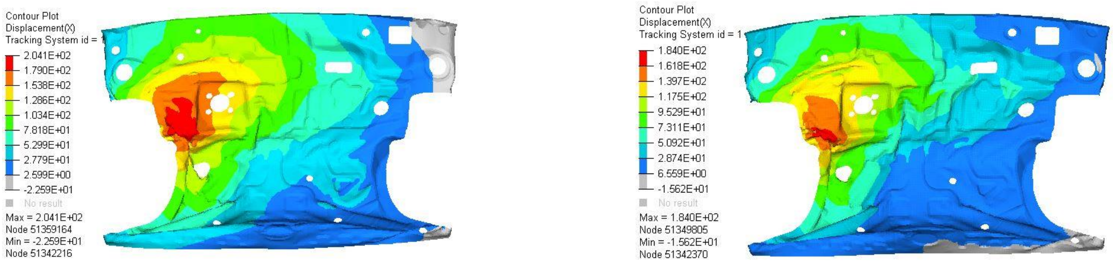
Figure 18. Comparison of body acceleration before and after improvement

As shown in Figure 19, the maximum penetration of the front panel before and after full-width frontal collision improvement decreases by 27%. The maximum intrusion of the front panel before and after offset impact improvement is 9.8% lower than that of the front panel as shown in Figure 20. Therefore, the improvement scheme will not adversely affect the other two frontal collision conditions.



（a）Before improvement **（b）After improvement**

Figure 19. Comparison of Front panel intrusion in 100% front collision



（a）Before improvement **（b）After improvement**

Figure 20. Comparison of Front panel intrusion in 40% offset impact

6 Summary

In this paper, the crashworthiness of a domestic Mini pure electric vehicle under 25% small offset crash conditions is studied by CAE simulation. The simulation results show that the passenger compartment is greatly deformed. Compared with full-width frontal impact and 40% offset impact, the overlap rate of body structure and barrier is lower in small offset impact. The main energy-absorbing components such as front anti-collision beam, energy-absorbing box and front longitudinal beam can not participate in the collision process. The backward extrusion of tires results in serious deformation of the whole passenger compartment. This paper optimizes the vehicle from two aspects of structure improvement and material reinforcement, and simulates the improvement scheme. The scheme greatly reduces the invasion of the passenger compartment, and has no adverse impact on the other two frontal collision conditions, and improves the collision safety performance of the vehicle.

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