Roof Strength Analysis of Electric Vehicle with CFRP Side Beam Based on LS-DYNA

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Abstract：Based on the weight characteristics of electric vehicles, this paper points out the difficulties and challenges of improving the roof strength in the field of electric vehicles. According to the mechanical properties of CFRP (Carbon Fiber Reinforced Polymer/Plastic), the importance of CFRP for lightweight and mechanical performance improvement of electric vehicle is elaborated. A finite element model for the roof strength analysis of CFRP upper-side beam based on LS-DYNA is established. The test of the BIW with CFRP upper side beam is carried out. The test results are consistent with the simulation results in macroscopic phenomena and load curve trends. By analyzing the difference between simulation and test, it is pointed out that the application of quasi-static material characteristics can make the simulation results more accurate.

Keywords：CFRP, Electric Vehicle, Roof Strength, LS-DYNA

1 Introduction

With the upgrading of resource structure and the change of travel habits of urban people, electric vehicles are widely accepted by the public. Compared with traditional fuel vehicles, electric vehicles have 20% to 30% heavier weight than the same grade fuel vehicles due to the integration of high-density power battery packs. Compared with traditional vehicles, the structure and performance of electric vehicles are more sensitive to weight characteristics. In the course of automobile driving, automobile rollover will be caused by steering or deviating from the road. Relevant statistical research shows that the fatality rate of automobile rollover accident is about 30%, which is higher than that of ordinary automobile accident [1] [2]. The roof structure with enough strength can effectively protect the occupants in the car and prevent the damage to the occupants caused by the deformation of the roof structure in rollover accidents. The weight characteristics of electric vehicles make the good roof strength performance a challenge.

In order to attach importance to the strength of passenger car roof, China revised GB26134-2010 ‘Roof crush resistance of passenger cars’ by referring to FMVSS216, which became a mandatory regulation for the strength of passenger car roof in 2012, requiring that the ratio of load to vehicle weight in limited crushing displacement should be greater than 1.5 times. C-IASI (China Insurance Automotive Safety Index) adopts the same grading evaluation system as IIHS in the United States. According to the ratio of strength to vehicle weight at 127 mm roof deformation displacement, the grading system of roof strength is established. The grading of roof strength is based on the SWR (Strength-to-weight ratio) of body load to vehicle weight measured in the range of 127 mm body deformation during the test process[3].See Table 1。

Table 1 Strength-to-weight ratio

SWR	Rating
SWR≥4	GOOD
4＞SWR≥3.2	ACCEPTABLE
3.25＞SWR≥2.5	MARGINAL
SWR＜2.5	POOR

In recent years, with the development of electric vehicles and the development of carbon fiber composites manufacturing technology, the cost of carbon fiber composites technology has gradually decreased, and related materials and processes have been widely used in electric vehicles [4] [5]. Compared with other materials, carbon fiber materials have better mechanical properties, such as high strength, specific modulus, low density, good fatigue resistance, good seismic performance and good corrosion resistance [6]. Three-dimensional braided CFRP parts forming is a braiding method which can directly produce fiber prefabricated parts from fibers. Compared with the traditional two-dimensional braiding method, the three-dimensional braiding technology reduces the manufacturing process and process cost. The application of this technology in automotive structure design, body parts processing and vehicle manufacturing will have a significant impact on the automotive industry.

In this paper, the application of CFRP A-pillar side beam structure in electric vehicle is studied, and the influence of carbon fiber material on the roof strength performance of vehicle is discussed. By comparing the simulation analysis with the test results, how to simulate the mechanical behavior of carbon fiber material more accurately in finite element simulation is discussed.

2 FE Model of BIW

2.1 BIW Model

According to the basic model of a listed electric vehicle, the roof strength analysis model with CFRP side beam is established. As shown in Figure 1, the model mainly includes BIW with CFRP upper side beam, closures (without glass) and loading rigid blocks. This model uses mm-ms-kg unit system. It has 1246820 nodes and 1146498 elements. The element size is 4-9 mm. The shell element is the main element type. The solver uses LS-DYNA and Belytschko-Ysay single point integration type. The total weight of the BIW and the closures parts is 415 kg.

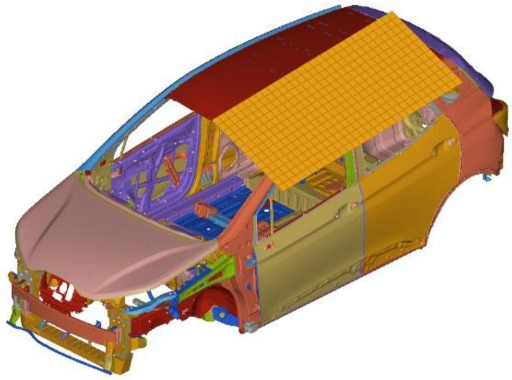

Fig.1 FE Model of Roof Crush Resistance

Fixed constraints are imposed on the lower edge nodes of the rocker on both sides of the BIW to block the movement and rotation of all degrees of freedom in order to fix the BIW. The loader is simplified as a rigid surface. During the simulation analysis, the loader is set to move in the plane normal direction. The velocity of the rigid surface is 1 mm/ms, and the simulation calculation time is 120 ms.

Because of the non-linearity of geometric deformation, material characteristics and boundary characteristics in the simulation process, the deformation process of vehicle roof is a complex non-linear process. In the simulation model, the constitutive model * MAT24 is used to simulate the isotropic elastic-plastic material. The high-speed tensile curves of different grades of metal material cards are included under different strain rates.

2.2 CFRP Side Beam Model

The CFRP finite element model of the upper side beam of the BIW is composed of two parts, the outer carbon fiber reinforced plastic pipe and the internal supporting foam, as shown in Fig. 2. The main structure load is borne by the structure of CFRP side beam, and the internal supporting foam acts as the setting support for manufacturing. CFRP side beam assembly is installed on top of A-pillar, B-pillar, and C-pillar of the BIW. CFRP side beam and the BIW are bonded together by glue. Compared with the commonly used high-strength steel structure, this structure can reduce weight and enhance the strength of the roof structure.

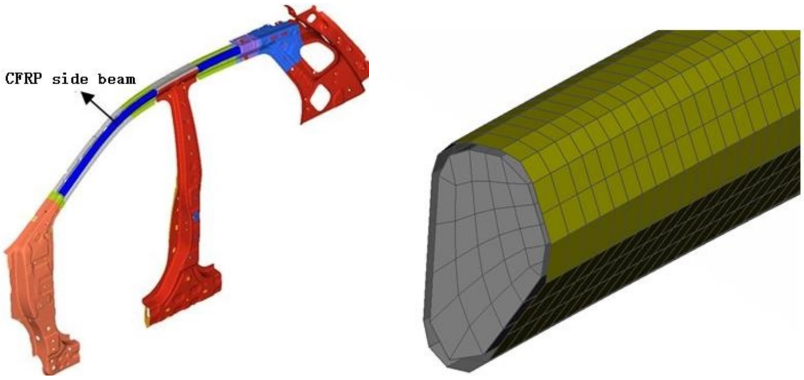

Fig.2 FE model of CFRP side beam

In the model, the structure of CFRP side beam is shell element, which is defined by * PART_COMPOSITE keyword. The keyword can define the properties of different layers of composite materials. In the keyword card, the thickness, material and fiber direction of different layers of CFRP side beam are defined. In order to calculate accurately, the integral method of CFRP shell element is defined as integral, and defined surface to surface contact between CFRP tube and internal supporting foam.

CFRP side beam material is carbon fiber reinforced composite plastics, which is anisotropic and strongly non-linear. LS-DYNA software platform has abundant material library models for anisotropic materials, and different material models have corresponding material failure criteria. The material model * MAT_058/* MAT_LAMINATED_COMPOSITE_FABRIC in LS-DYNA is selected for simulation. The material model can be used to simulate composites of unidirectional laminates, laminates and fabrics. For shell elements, the material model is a continuous medium damage model, and the failure rule is based on Hashin failure criterion [7].

Hashin failure criterion considers the four failure modes of fiber tension and compression, matrix tension and compression cracking. The complex and diverse damage modes of carbon fiber composites are judged. The failure criterion of the failure plane in Fig. 3, and the failure model is as follows [8] [9]:

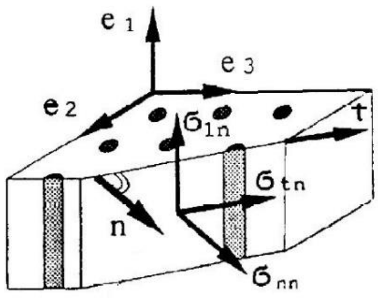

Fig.3 Failure planes of the lamina

When $\sigma_{11} \geq 0$,

$$e_m^2 = (\frac{\sigma_{11}}{X_t})^2 - 1 > 0 \rightarrow \text{Failure} \quad (1)$$

When $\sigma_{11} < 0$,

$$e_c^2 = (\frac{\sigma_{11}}{X_c})^2 - 1 > 0 \rightarrow \text{Failure} \quad (2)$$

When $\sigma_{22} \geq 0$,

$$e_m^2 = (\frac{\sigma_{22}}{Y_t})^2 + (\frac{\tau}{S_c})^2 - 1 > 0 \rightarrow \text{Failure} \quad (3)$$

When $\sigma_{22} < 0$,

$$e_d^2 = (\frac{\sigma_{22}}{Y_c})^2 + (\frac{\tau}{S_c})^2 - 1 > 0 \rightarrow \text{Failure} \qquad (4)$$

In the above equations, X_t is the longitudinal tensile strength, X_c is the longitudinal compressive strength, Y_t is the transverse tensile strength, Y_c is the transverse compressive strength and S_c is the shear strength. Equation (1) is the failure criterion of fiber tension, equation (2) is the failure criterion of fiber compression, equation (3) is the failure criterion of matrix tension and equation (4) is the failure criterion of matrix compression. Four formulas exist independently to judge different damage conditions. Independent failure criterion can judge the failure of laminated fiber composites.

The roof strength model is analyzed and calculated, and the results are shown in Fig. 4.

Fig.4 Analysis of roof crush resistance with CFRP side Beam

Fig. 5 shows the load-displacement curve of CFRP side beam roof strength analysis. The maximum load is 41KN. The vehicle's complete weight is 1650 kg, and the SWR is 2.52, which meets the requirements of GB standard. It belongs to the 'MARGINAL' level of IIHS and C-IASI evaluation.

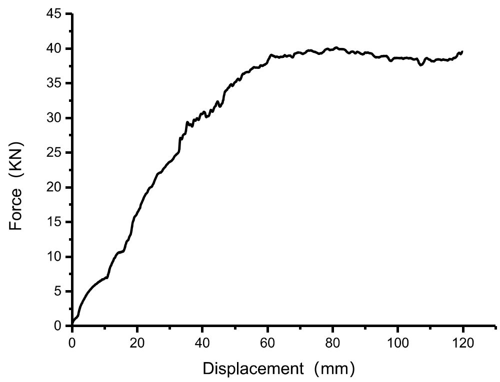

Fig.5 Load-Displacement Curve of CFRP side beam

Figure 6 shows the deformation state of the CFRP side beam. The red frame represents the initial position. It can be seen that the CFRP side beam has good integrity and no large bending deformation. CFRP beams are intact without damage and failure, while the surrounding metal structures undergo bending deformation due to large loads. From this, it can be seen that the stiffness advantage of the CFRP beam is obvious, and the use of CFRP material in the body bearing structure can increase the local structural stiffness.

Fig.6 CFRP side beam deformation

3 Test of Roof Strength

According to the test requirements of GB26134-2010, the roof strength test of BIW with CFRP upper side beams is carried out, as shown in figure 7.The test is carried out according to the parameters in Table 2, and the vehicle status after the test is ready is shown in Figure 8.

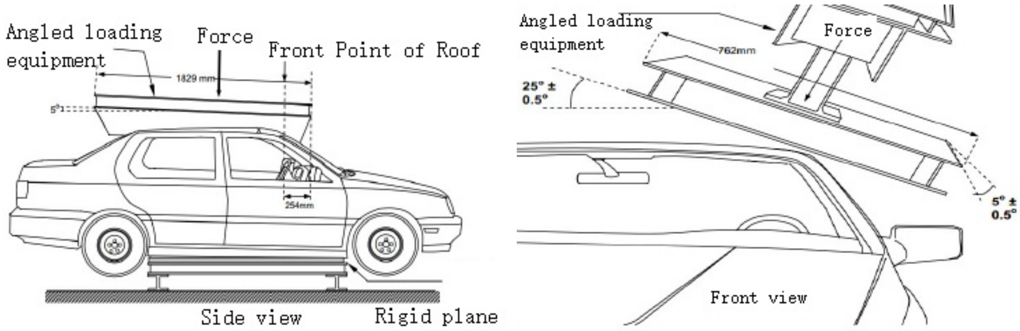

Fig.7 Test requirements

Table2 Test parameter setting

Test parameter	Setting values	Test parameter	Setting values
Load（KN）	170	Maximum deformation（mm）	300
Loading velocity（mm/s）	5.0	Unloading velocity（mm/s）	5.0
Initial load（N）	30	Alarm coefficient	1.5

Fig.8 Experimentation state indication

Figure 9 shows the load-displacement curve measured by the test. The maximum load measured by the test is 35.5KN, and the SWR is 2.19.

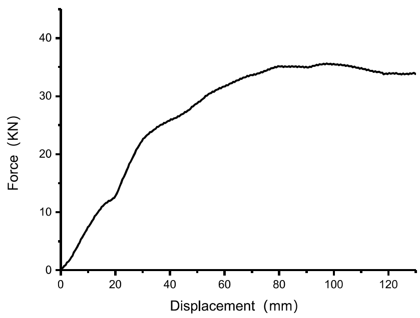

Fig.9 Test Load-Displacement curve

Fig. 10 is a comparison between the experimental results and the simulation analysis animation. It can be found that both the simulation and the experiment have obvious failure at the right roof and the connection between the left roof and the side wall, and the A and B pillars have obvious bending, which proves the rationality of the simulation and the experiment from the macroscopic phenomenon.

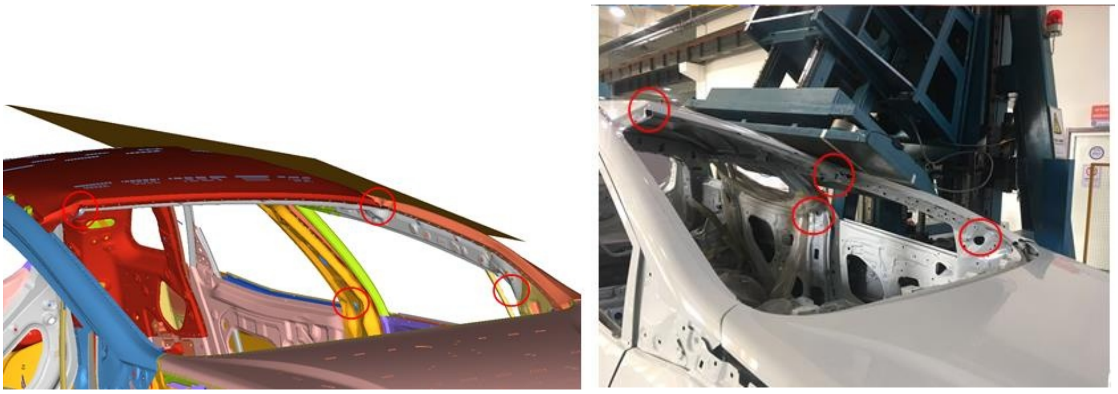

Fig.10 comparison of simulation and experiment phenomena

Fig. 11 is a comparison between the experimental curve and the simulation analysis curve. The two curves have good similarity before 30mm. After analysis, it can be judged that the simulation model can better respond to the load change in the elastic stage of material properties. But after 30 mm, there are differences between the test and the simulation analysis. The simulation analysis value is larger than the test value, and the error is large, which can not accurately reflect the real situation of load change.

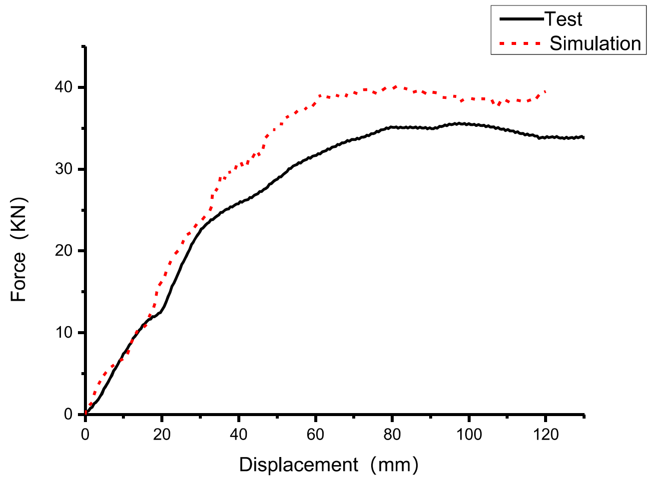

Fig.11 Comparison of simulation and test curves

4 Result Analysis

From the difference analysis of simulation analysis and experiment, it can be seen that in the latter half of the curve(entering the stage of large plastic deformation), there are great differences between the experiment and simulation analysis. After analysis, it can be inferred that one of the important factors for the difference between simulation analysis and experiment should be the difference caused by material properties. In general conventional analysis, the material model of collision analysis usually takes several strain rate curves at different rates to cope with the high-speed deformation in simulation analysis. However, the loading speed of the roof strength test is generally less than 10 mm/s, which is close to the quasi-static test.

Based on the above analysis, the material models in the simulation model are replaced by quasi-static material curves. The simulation results are compared with those in Figure 12. The load curve calculated by the quasi-static material characteristic model is in good agreement with the test curve. This proves that the quasi-static material model can more accurately reflect the change of the load in the roof strength analysis.

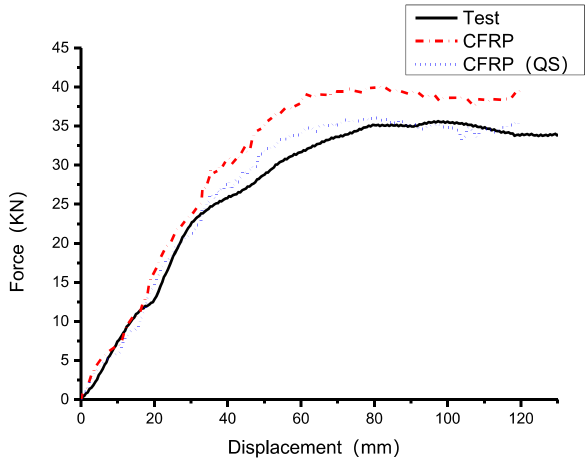

Fig.12 Comparison of simulation and test curves

5 Conclusion

In this paper, the influence of CFRP side beam structure on the roof strength of electric vehicle is studied by means of finite element simulation analysis and experimental verification. Through the above analysis, there are several conclusions.

(1) Through simulation analysis and test validation, the application of CFRP side beam structure can effectively meet the roof strength requirements of GB standard, and is conducive to vehicle lightweight design, which is of great significance in the design of electric vehicle.

(2) In the analysis of the top compressive strength, the quasi-static material model can be used to analyze and calculate more closely to the test results and improve the accuracy of simulation analysis.

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