Optimization of Vehicle Structure for High-speed Rear-end Impact

Tang Chaoqun[1], *Jikuang Yang*[1, 2]
(1.State Key Laboratory of Advanced Design and Manufacture for Vehicle Body, Hunan University, Changsha, 410082, China;)
(2.Department of Applied Mechanics, Chalmers University of Technology Gothenburg, Sweden41296)

Abstract: The study aimed to optimize the vehicle crashworthiness in rear impact by using orthogonal experimental design (OED) and comprehensive equilibrium methods. Firstly a finite element model of a full-scale vehicle in rear impact was developed. Then we made a high-speed rear impact simulation according to the rules of new FMVSS301. In order to improve the vehicle crashworthiness, the effects of 4 parameters (thickness and type of material of rear rail and rear bumper) on integrity of fuel system of vehicle were considering three criterions. The main criterion was the maximum effective strain of fuel tank, and the secondary criterions were the weight and the energy-absorbing capability of rear rail and rear bumper. The results from the study showed that the optimal parameters are as follow: material of rear rail is DP800 with thickness of 1.5 mm, material of rear bumper is DP1000 with thickness of 2.0 mm. In this configuration the maximum of the effective strain of fuel tank is reduced by about 50%.
Key words: rear impact, OED, comprehensive equilibrium method, structure optimization

1 Introduction

Rear accident is not one of the major categories of the urban road traffic accidents, the incidence rate is less than the front and side impacts. However, according to the 2005 road traffic accident statistics from China, this type of accidents accounts for 12.88 % of all accidents with death ratio of 14.77%, and this type of accidents is ranked first, as high as 30% of all accidents, on national freeways [1]. Moreover, the fires resulting from fuel spillage are likely to happen in this type of accidents and can lead to additional property losses. So in China has been paid to more and more attention to the problem of rear impact. On July 1, 2006, the Chinese government approved a standard named “The requirements of fuel system safety in event of rear-end collision for passenger car” (GB20072-2006) [2]. In the standard, the velocity of collision is only 50 km/h, while 80 km/h is required as the collision speed in the new Federal Motor Vehicle Safety Standard No.301 from 2008. The US new standard increased requirement for the crashworthiness and the integrity of fuel systems of vehicle.

Zhu et al. [3] pointed out that in China a little research had been conducted in crashworthiness of rear structure of vehicle because the requirements of rear impact had been used only a short time. Therefore, there is much work to do in the term of crashworthiness of rear impact. In the current study we developed a finite element model of rear collision of a certain car based on the requirements of the new FMVSS 301. At the meantime we confirmed three criterions to evaluate the vehicle crashworthiness. By means of OED and comprehensive equilibrium methods, the parameters related to the thicknesses and materials of rear-rail and rear-bumper could be optimized, the risk of fuel spillage reduced.

2 Methodology

2.1 Selection of design parameters

To improve crashworthiness of rear structure of vehicle and to study the influence on the integrity of fuel systems, we decided to select fore following parameters to optimization procedure as shown in Table 1. All selected parameters were investigated at three different levels.

Table 1 Levels of Design Parameters

	Design Parameter	Level 1	Level 2	Level 3
A	Material of rear rail	DP600	DP800	DP1000
B	Thickness of rear rail	1.5 mm	1.8 mm	2.0 mm
C	Material of rear bumper	DP600	DP800	DP1000
D	Thickness of rear bumper	1.2mm	1.5 mm	1.8 mm

One of the parameter was material of rear rail. We selected three materials that have different yield strengths. The parameters regarding mechanical properties of selected materials are summarized in Table 2.

Table 2 The parameters of materials

Materials	Parameters			
	Density [kg·m^{-3}]	Elastic modulus [GPa]	Poisson ratio	Yield stress [MPa]
DP600	7.90 e+3	210	0.3	423.4
DP800	7.83 e+3	210	0.3	455.4
DP1000	7.85 e+3	210	0.3	707.0

2.2 Selection of criterions

The crashworthiness of vehicle in rear impact is directly related to the integrity fuel system and stability of rear structure. However, it is difficult to judge if there is a fuel spillage during the impact simulation for the reason that fuel is unable to simulate by CAE technology. Therefore, we considered the max effective strain of fuel tank as the main criterion to estimate the integrity of fuel system. Considering cost-efficiency and the energy-absorbing capability, we took the masses and the energy-absorbing capability of rear rail and rear bumper as the secondary criterions.

2.3 Selection of optimization methods

The way to optimize design parameters was divided in two steps. Firstly, parametric analysis was done using orthogonal experimental design method [4]. Secondly, comprehensive equilibrium method [5] was applied to solve the optimal matching scheme.

Orthogonal experimental design is a multi-factor optimization method of experimental design, which selects some representative and orthogonal samples to do experiment. The method can find the best match between the levels of factors or deduce the optimal match from the experimental results by means of several experiments. The experiments are arranged by orthogonal array. Normally the orthogonal array L is expressed as $L_n(a^p)$ where p is the number of columns, a is the number of levels of experiment. The orthogonal experimental design is shown in Table 3.

Table 3 Orthogonal experimental design

Test No.	Factors			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	2
6	2	3	1	1
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Comprehensive equilibrium method was used to multi-objective analysis of experiment. Since the important degree of criterions was inconsistent, the influence from different factors on criterions was also different. By using the comprehensive equilibrium method, we can analyze single criterion directly in the first place to get the influencing order. We considered the reference value such as range value (R) and average conversion rate of each factor value (K). The value of R reflects the influence degree of design parameters on criterion. When R value is higher the influence of the parameters is greater. These results we compared then with theoretical knowledge and practical experience we can select the levels of design parameters.

2.4 Model preparation for simulation

2.4.1 Establish of vehicle finite element model

In the study we decided to make optimization of a foreign car that mesh was available in laboratory and was detailed enough for the purpose of the study. The original model was taken from NHTSA database. After re-meshing the car body in white, the suspension system, power-train, exhaust system, doors, fuel tank, trunk lid and other components were combined into a whole model. In the model, solder joints were used to connect parts and some bolts was replaced by rigid units. The relationships of mechanical constraints in real motion were expressed well by using rotating and ball hinges connection.

Changing strain rate can affect the plasticity behaviors of elastic-plastic materials. The influence of strain rate on the property of material must be considered in high speed impact because high rate of strain is the cause of hardening of elastic-plastic materials. In the study Cowper-Simons model was applied to consider the influence of this phenomenon.

2.4.2 Simulation condition

According to the new FMVSS301 requirement, the rear impact simulation analysis was done. The vehicle was impacted from the rear by a barrier moving at 80 km/h with 70% overlap, as shown in Figure 1.

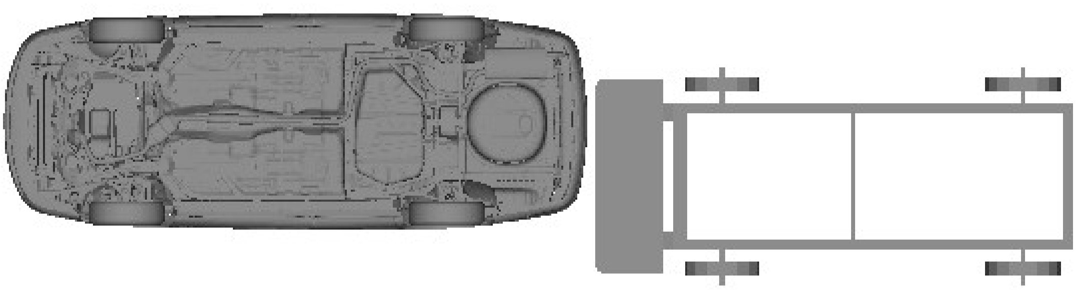

Figure 1 Model of rear impact

3 Influence of parameters on criterions

3.1 Analysis of parameters on the max effective strain of fuel tank value

The influence of the parameters on the max effective strain of fuel tank value is shown in Table 4. The order of this influence is as follows: thickness of rear bumper (D) > material of rear rail (A) > material of rear bumper (C) > thickness of rear rail (B).

Table 4 Analysis of maximum effective strain of fuel tank value

Evaluation Indicators		A	B	C	D
maximum effective strain of fuel tank	K1	0.5789	0.5299	0.5371	0.5972
	K2	0.4848	0.5151	0.4444	0.5546
	K3	0.4659	0.4847	0.5481	0.4378

When the thicknesses of rear rail and bumper increase (B and D1-3), the value of maximum effective strain of fuel tank is reduced, see Figure 2.

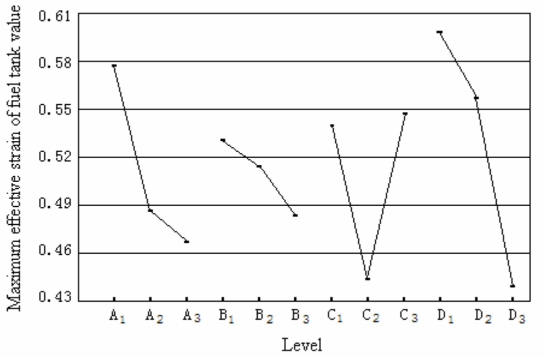

Figure 2 Level trend line of maximum effective strain of fuel tank value

3.2 Analysis of parameters on total mass

The influence of the design parameters on total mass is shown in Table 5. The order of the influence is as follows: thickness of rear rail (B) > thickness of rear bumper (D) > material of rear rail (A) > material of rear bumper (C).

Table 5 Analysis of the total mass

Evaluation Indicators		A	B	C	D
total mass(kg)	K1	19.22	17.22	19.20	17.82
	K2	18.99	19.27	19.01	19.04
	K3	19.02	20.67	19.03	20.38
	R	0.20	3.38	0.19	2.56

The thicknesses of rear rail and rear bumper are significant parameters. As the thicknesses increase (B and D1-3), the total mass increases greatly, influence of the other parameters are lower than that of thicknesses (Figure 3).

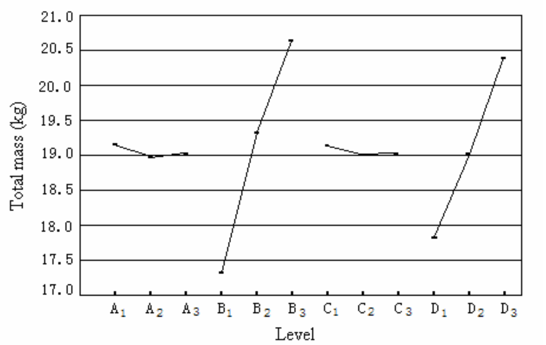

Figure 3 Level trend line of total mass

3.3 Analysis of parameters on total energy-absorption

The influence of the design parameters on total energy absorption is shown in Table 6. The order of the influence is as follows: material of rear bumper (C) > thickness of rear bumper (D) > thickness of rear rail (B) > material of rear rail (A).

Table 6 Analysis of the total energy absorption

Evaluation Indicators		A	B	C	D
total energy(KJ)	K1	26.05	26.94	27.98	27.22
	K2	26.78	27.17	26.15	26.92
	K3	25.44	24.17	24.14	24.13
	R	1.34	3.0	3.84	3.09

Figure 4 shows that when the yield strength of material of rear bumper is increasing (C1-3), the total energy-absorption is reduced sharply.

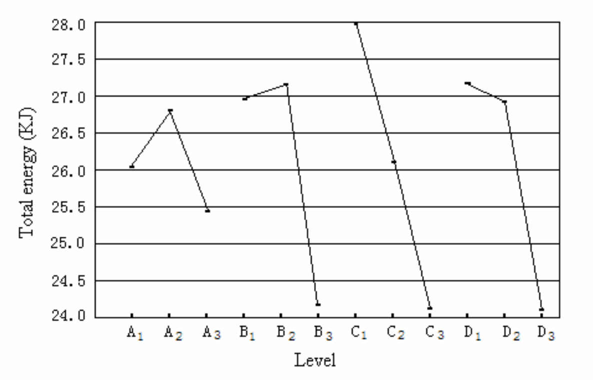

Figure 4 Level trend line of total energy-absorbing

4 Selection and determination of optimization procedure

According to the importance of design parameters on different criterions, we chose the level of factors using comprehensive equilibrium method. The influence of D factor on the main criterion is strong therefore D3 level was adopted. The factor C has small influence on increased mass, and value of main criterion is the minimum for C2 so this level was chosen. The B factor is the main one influencing the increase of mass at the same time influence slightly other criterions, B1 level is adopted as a compromise between the analysis and economy cost. Factor A shows a major influence on main criterion, while the total energy-absorption first increases and then decreases as A value increasing. Taken into consideration that energy-absorption capability will influence the deformation of structure around fuel system, there is a contradiction between the selection of level A2 or A3. Temporarily we adopted both levels of A2 and A3. So the FE simulation of Test No. 4 (A2B1C2D3) and new configuration Test No.10 (A3B1C2D3) will be done to choose the optimization procedure. From the analysis of comprehensive equilibrium method, the combination A2B1C2D3 is the best configuration of the nine orthogonal experiments.

Table 7 and Figure 5, 6 and 7 show the results of Test No. 4 and Test No. 10 compared with simulation of original structure.

Table 7 Compare of data before and after improvement

Scheme	Maximum effective strain of fuel tank value	Total energy [KJ]	Total mass [kg]
Originally structure	0.6409	30.51	15.90
Test No. 4	0.3673	25.11	18.44
Test No. 10	0.3208	23.84	18.47

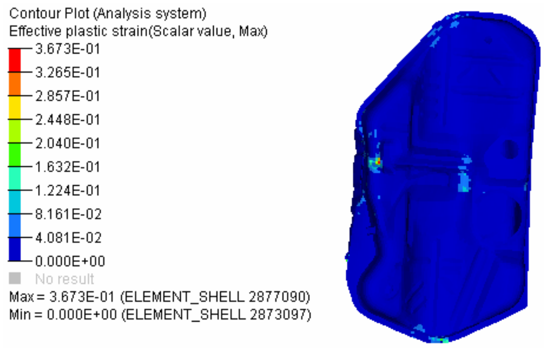

Figure 5 Maximum effective strain of fuel tank value of Test No. 4

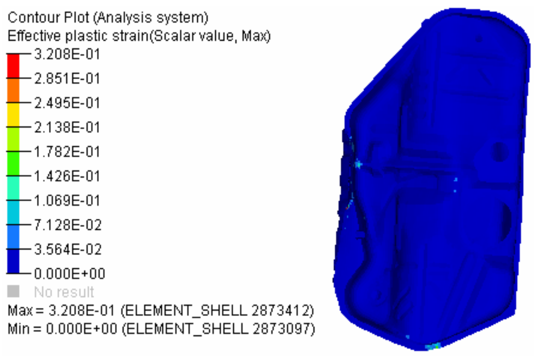

Figure 6 Maximum effective strain of fuel tank value of Test No. 10

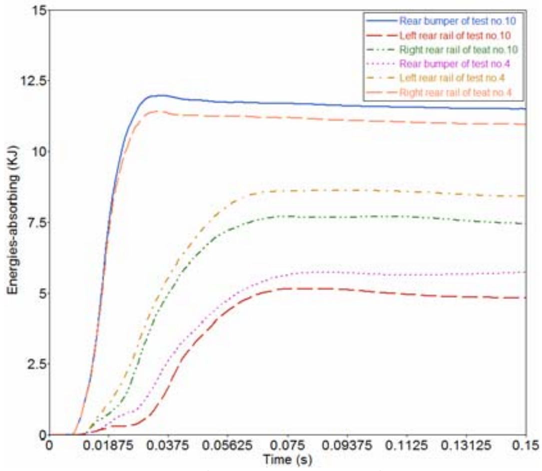

Figure 7　Comparison of energy-absorption of rear structure

According to the calculated results presented in Figure 5 and Figure 6, the maximum effective strain of fuel tank after improvement in Test No. 4 and Test No. 10 decreased by 42.69% and 50.07%, respectively. Besides, the absorption of total energy decreased by 17.7% and 21.86%, respectively, see Figure 7. The mass increased in Test No. 4 is close to the results of Test No. 10.

Because the effective strain of fuel tank is the main considering criterion in the paper, as well as the discrepancy of increasing of total mass and total energy absorbing is not significant, the set of factor levels from Test No. 10 would be selected as the optimal combination.

Compared the optimal results with the originally results, the integrity of fuel system was improved greatly; however, the weight of vehicle was increased slightly that can influence the cost-efficiency. However, using the procedure of current study in optimization of whole vehicle we can also decrease the weight.

5　Conclusion

Regulation FMVSS301 mainly considers the integrity of fuel system to prevent human casualties and property losses as a result of fuel spillage in rear impact. In the study, the material and thickness of rear rail and bumper were optimized based on the FMVSS301. The orthogonal experimental design (OED) and comprehensive equilibrium methods were used to reduce the number of experiments. The approach of mathematical simulations combined with optimization procedures used in current study is very usable in the design of structure considering the improvement of vehicle crashworthiness.

Reference

[1] The Ministry of Public Security Traffic Administration (2005). The People’s Republic of China Road Traffic Accidents Stat. Data Compilation. (In Chinese).
[2] The State Administration of Quality Supervision Inspection in Quarantine (2006). The requirements of fuel system safety in event of rear-end collision for passenger car (GB20072-2006). (In Chinese).
[3] Zhu, P., Xiao, G.F., Zhang, Y., Shi, Y.L. (2008). Rear - end Collision Simulation and Improvement of Structural Crashworthiness. Chinese Mechanical Engineering. (In Chinese).
[4] Luan, J. (1987). Techniques and Methods of Experimental Design. Shanghai Jiaotong University Press, Shanghai (in Chinese).
[5] Li, Y.Y., Hu, C.R. (2005). Experimental Design and Data Processing. Academic Press, Beijing (in Chinese).