Optimization of Crashworthiness of Rear-End Structures of Vehicle

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Abstract: The optimization of rear end structures of the vehicle including the rail, the extension of the rail and the crash box was performed according to "Passenger cars rear–end fuel system safety requirements" GB 20072-2006 using FE model of the whole car that was developed based on a certain passenger car from a local manufacture. Through the application of multi-objective algorithm, the thickness of rear rail and the rear crash box was optimized. After the optimization, the maximum effective plastic strain of the fuel tank was reduced by 10.3%, the energy absorption of the extension of rear rail and rear crash box increased by 13.8%, the deformation of the rear suspension area was reduced by 45.3%. Thus, it is effective to reduce the risk of oil leak and improve the crashworthiness of the rear impact, while the research provides a certain reference value for improving rear-end structures.

Keywords: rear impact; FE model; multi-objective algorithm; optimization

1. Introduction

Rear-end, front and side impacts are constantly common forms of road traffic accidents in our country. The incidence of the rear-impact is third only to front and side impact [1]. To evaluate the crashworthiness of the vehicles in China the regulation "Passenger cars rear–impact fuel system safety requirements" GB 20072-2006 was issued on 1st, July, 2006, which requires vehicles manufactured to meet it, but little research about vehicle response in rear-end impact has been done. Most of manufactured vehicles meet regulations, but research on crashworthiness in the rear-end impact is still desirable and this research is crucial.

There are some methods to improve crashworthiness of the components that were investigated in our country, The methods of thickening rear rail and the extension of this structure proposed by Yang Zhigang[2]. Also Zhu Ping[3] and his team evaluated effects of setting induction slot, reinforcing plate and "false" plastic hinge in rear tail. All changes they investigated were proved to be effective. Another method to improve crashworthiness can be the use of high strength steel. This was evaluated by Li Baojie[4]. He found that it could bring desirable results, but cost of the whole car would be increased.

Therefore in the study, considering minimizing the cost and light-weighting requirement of the whole vehicle its structural components in rear-end impact, we selected the thickness of rear rail, the extension of rear rail and energy crash box and optimized through multi-objective algorithm. Our goal was to improve the safety in rear-end collisions by modification the of the fuel system with smallest change of whole vehicle cost and weight.

The optimization of rear end structures vehicle performed according to GB 20072-2006 using FE model of the whole car that was developed based on a certain passenger car from a local manufacture.

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2. Methodology

2.1. Preparation of FE Models and Selection of Scope of Investigation

For the optimization, in the study we selected certain local manufactured passenger car. The FE model of this vehicle was built through Hypermesh software as shown Figure 1. The model of the vehicle includes 907074 nodes and 7685 link-elements.

The model of the car was used in collision with the trolley. The model of trolley we used was obtained from the Shanghai Automobile Measuring Centre as shown in Figure 1. The model is built according to GB 20072-2006. The front of the trolley is 2600 mm wide, 800 mm high; the level from ground is 185 mm and the weight 1119 kg. The position of the centre of gravity in vertical direction is 484 mm from the ground. In the horizontal plane the centre of gravity is 61 mm behind the axle of the front wheels and is 3 mm right-skewed from longitudinal axis.

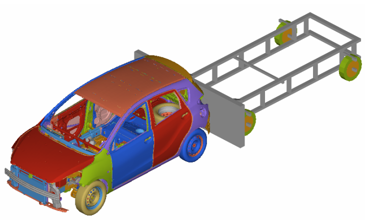

Figure 1. Rear-end impact FE model

It was decided that whole car FE model needs to meet the requirement of the verification through real vehicle experiment. This experiment was performed according to GB 20072-2006, the speed of the trolley was 50 m/s and the axis of trolley and the car was on the same line, see Figure 2.

We validated the model by comparison of acceleration curves of left B-pillar the between simulation and test in rear-impact, see Figure 2. These curves show the same time duration of the pulse and similar average acceleration. We can see differences of the 2 curves in the first top value which may be caused by vibrations at the beginning of the crash test. Thus, FE model in the research is reliable, which can be applied in analysis of rear-end impact.

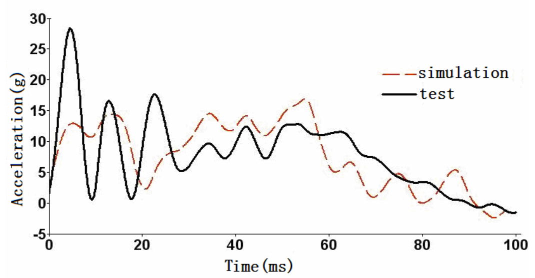

Figure 2. Acceleration curves

In our country, rear-end impact regulations has been issued, but rear-end impact is not included in assessment procedures of new vehicles by CNCAP. Therefore, in the trend of economization and light-weighting design, numerous car makers use the way of lighting the structural components of the rear part of the vehicle and this is not evaluated by CNCAP. As example that is shown in Figure 3, improving of rear rail a certain local manufactured car was lightened, but this improvement was only confined to size reducing of the reinforcing plate. In the study we selected this car for optimization.

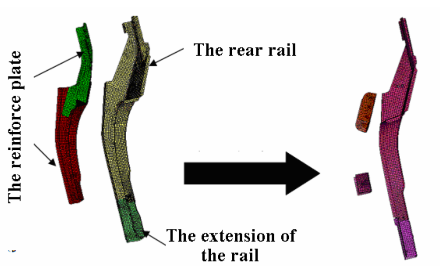

Figure 3. Lightening of a certain local manufactured car

According to traffic accident analysis, oil leaking is mainly caused by oil tank suffering so called first or second crash. According to the definition of Yang Zhigang [2] and his team, first crash is that the structure of the vehicle couldn't maintain integrity and squeezes the oil tank even makes it cracking in the process of rear impact; second crash is that certain fragile components such as the swing arm in rear suspension area and rear axle related to chassis produces sharp objects due to large deformation during impact, which plunge and punctures fuel tank. Hence, the main target of safety design is how to avoid first and second impact.

To improve the safety in rear-end impact the roles of structural components in first and second crashes are important. Therefore from validation simulation and high-speed video from the test we made the analysis of the influence of strength of various components of rear-end area on deformation of fuel tank.

(1) In first crash, unreasonable design of rear-end impact structure may directly cause the squeezing of fuel tank and extreme plastic strain, even oil leaking. Consequently, structural components around the fuel tank should be designed to resist certain impact loads. In design, main energy absorbing parts of car, such as the extension of the rail and energy crash box. These parts need absorb enough energy to alleviate the impact that the fuel tank suffering.

(2) It is difficult to verify the damages of the fuel tank through simulation in the second crash. It is because large deformations exist in rear suspension area (Figure 5, area 2) and components of this area absorb much energy which reduces the maximum effective plastic strain of the fuel tank. On the contrary, these deformations could produce certain sharp objects that would damage fuel tank actually, and also lower the crashworthiness of rear structure. The strength of the rear area of the car couldn't be too great, otherwise energy absorption would be ineffective and cause high acceleration of the car and increased maximum effective plastic strain of the fuel tank. Hence, rigidity of this part needs a proper design.

The results from impact test and simulation performed for the validation of the rear-end collision we analyzed before optimization process to find deficiency of initial structure regarding safety as shown in Figure 6 and Table 1. Rear rail is weak in suspension area (area 2 in Figure 4). In this area under the action of force and torque Ma, large inward bending moment occurred at point C, which caused large deformation. The value of this deformation ($\Delta L2$) is 73 mm. As shown in Figure 5 downward bending moment occurred at point A and car body was lifted, which made the fuel tank squeezed, the maximum plastic strain (ε) of the fuel tank is 0.4181. The area 3 around the fuel tank, under the action of torque Ma and Mb, began to turn. These deformations in area 2 and 3 were observed because not enough energy was absorbed in area 1. The energy absorption (E) in this area of the crash box and the end part (extension) of the rail was only 16 578 J.

Table 1. Results from the simulation

ε	E [J]	$\Delta L2$ [mm]
0.4181	16 578	73

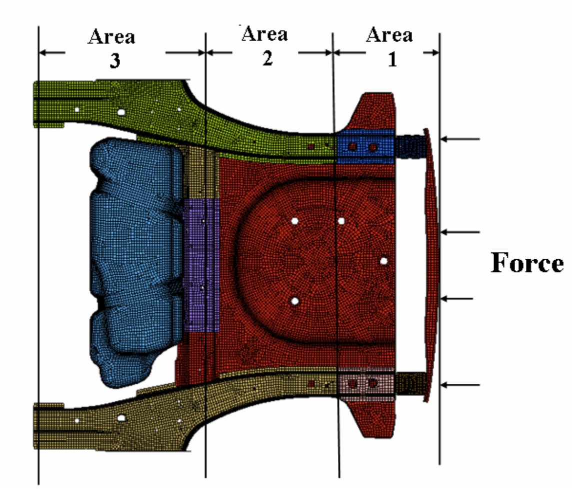

Figure 4. Main structures of rear part of the vehicle

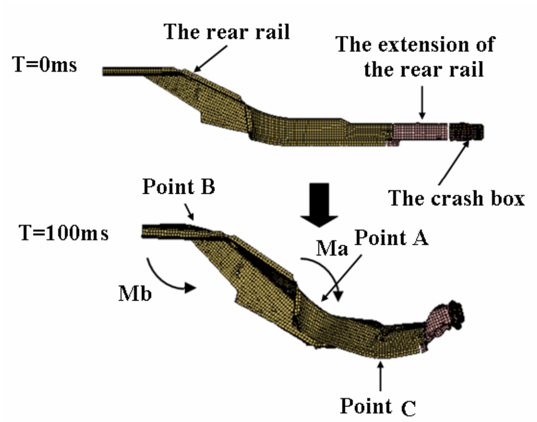

Figure 5. Deformation of main structures

2.2. Optimization

In the safety analysis at rear impact, the maximum effective plastic strain of the fuel tank is main factor to take in account. Therefore we choose the maximum plastic strain of the fuel tank (ε) as the safety criterion of the first impact. Regarding the energy absorption (E), we considered the extension of rear rail and crash box as the main components of the rear part of the vehicle. At last, we choose deformation (ΔL2) of the area of the rear suspension (area 2) to predict the safety level of the second impact. Then ε . ΔL2, E was considered as the target value to assess the design level of main components of the rear part of the vehicle.

According the simulation analyses, the lower the maximum value of the plastic strain (ε) of the fuel tank and the more the energy is absorbed, the structure of the rear part of the vehicle is better, so we decided to use Min (ε), Max (E) as target values in multi-objective optimization. According to actual experience, the deformation the area of the rear suspension was chosen to be between 20 mm and 40 mm.

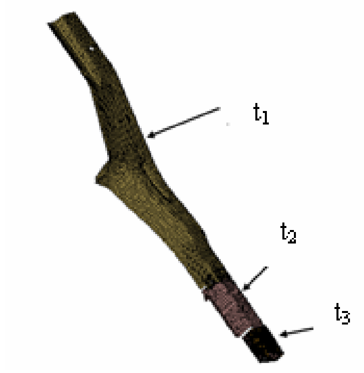

Figure 6. The structure for optimization

In the study, we chose the thickness of the rear rail (t_1), the thickness of extension of rear rail (t_2) and the thickness of crash box (t_3) as three design variables. According to the vehicle test and rear impact simulation analysis, the rear rail must be reinforced, and then the range of the thickness was selected between 1.6 mm and 2.2 mm. The thickness of the extension of the rear rail was changed a little from the original one; we selected it between 1.4 mm and 1.8 mm. The crash box must be also reinforced to improve ability of energy absorption, so range of the thickness was selected from 1.2 mm to 1.5 mm. In the present study, the multi-objective mathematical model of optimization problem is defined as follows:

Table 2. Multi-objective problem

design variable(mm)		
$1.6 \le t_1 \le 2.2$	$1.4 \le t_2 \le 1.8$	$1.2 \le t_3 \le 1.5$
target value		
Min(ε)	Max (E) J	20 mm≤ΔL2≤40 mm

The whole multi-objective optimization method contains three steps as follow:

(1) Design of experiment (DOE).
(2) Mathematical surrogate model.
(3) Multi-objective genetic algorithm (GA).

2.2.1 Design of Experiment

At first, we must obtain adequate design samples for the mathematical method. If want to calculate the coefficients of the this method, we must select enough design samples. In the study, we choose the method called the $L_9(3^4)$ orthogonal experiment to obtain enough sample points[5].

The orthogonal experiment can select part of representative sample points from the overall experiment, which are orthogonally. This process can find out the optimal match of the design variables though less experiments.

In the study we choose t_1, t_2, t_3 as three design variables. According the $L_9(3^4)$ orthogonal experiment, nine simulations must be done and the initial simulation. In total, we performed 10 simulations as shown in Table 3

Table 3. The design samples

NO.	t_1 (mm)	t_2 (mm)	t_3 (mm)	ε	E (J)	ΔL2 (mm)
1	1.6	1.4	1.2	0.3393	15887.8	54.0
2	1.6	1.6	1.3	0.3933	16993.3	74.0
3	1.6	1.8	1.5	0.4246	12932.4	149
4	1.8	1.4	1.2	0.3722	16957.4	34.0
5	1.8	1.6	1.3	0.3751	18877.1	39.0
6	1.8	1.8	1.5	0.3455	17395.7	124
7	2.2	1.4	1.3	0.5008	18144.8	14.0
8	2.2	1.6	1.5	0.4137	19620.6	11.0
9	2.2	1.8	1.2	0.4270	20477.3	9.00
10	1.6	1.6	1.2	0.4181	16578.2	73.0

2.2.2. Mathematical Surrogate Model

The response surface model of quadratic polynomial function was chosen as the surrogate model, which is applied widely in engineering optimization area, as a global approximation model [6].

The model is as follow:

$$f(x) = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x_i^2 + \sum_{j \le i}^{n} a_{ij} x_j x_i$$

where: $f(x)$ is the target function, n is the total number of design variables, x_i is the ith design variable, and the a is the unknown coefficient of each polynomial term. With the data from Table 3, we can construct the surrogate model of the ε, ΔL2 and E as follow：

$$\begin{aligned}
\varepsilon &= 0.411729t_1 + 0.326644t_1^2 + 0.316246t_2^2 \\
&-0.68458t_1t_2 - 0.087976t_2t_3 \\
\Delta L2 &= 50621.43 - 48016.5t_1 - 60111.9t_2^2 \\
&-94093.7t_3^2 + 20320.1t_1t_2 + 21024.79t_1t_3 \\
&+124708.9t_2t_3 \\
E &= -1258.76 + 535.156t_1 - 3420.65t_2 \\
&+5211.365t_3 - 145.215t_1^2 + 1321.384t_2^2 \\
&-772.646t_3^2 + 303.768t_1t_2 - 489.481t_1t_3 \\
&-1102.68t_2t_3
\end{aligned}$$

The fitting accuracy of the surrogate model is described by the coefficient of determination R^2 and adjusted coefficient of determination R^2_{adj} .The smaller the absolute value $\left|R^2 - R_{adj}{}^2\right|$, the more high the fitting accuracy and the smaller the error of the surrogate model.

In the surrogate models above, the determination coefficients R^2 of the three mathematical models are: 0.996, 0.997, and 0.972, the adjusted determination coefficients R^2_{adj} are: 0.991, 0.994, and. 0.945. The absolute value $\left|R^2 - R_{adj}{}^2\right|$ of the three surrogate models are 0.005, 0.003, 0.027, so the fitting accuracy of three surrogate mode is high. The surrogate models meet the requirements of prediction accuracy, can replace finite element model in the optimization process.

3. Results and Discussion

In the current study we used NSGA-II. The advantages of the algorithm are that it can find optimal solution as following [7]:

(1) Reduce the complexity of the algorithm, by Fast Non-Dominated Sorting.

(2) Proposed congestion of comparative factors, can find out the better one, which have the same virtual fitness value.

(3) Introduction of elite strategy, make the sample space widely and can select the best factor from the “Parents” into “Offspring”.

Based on these advantages above, the study use NSGA-II from iNSIGHT Software, the Pareto solution set obtained through 100 iterations of genetic algorithm contains 30 Pareto’s points, as shown in Table 4.

Table 4. The pareto optimal solution set of multi-objective genetic

No	t_1 (mm)	t_2 (mm)	t_3 (mm)	ε	ΔL2 (J)	E (mm)
1	1.853	1.600	1.298	0.377	39.86	19044.54
2	1.848	1.613	1.297	0.377	39.55	19072.84
3	1.848	1.605	1.297	0.377	39.94	19019.64
4	1.857	1.610	1.299	0.378	39.40	19151.05
5	1.864	1.617	1.301	0.379	39.15	19261.61
6	1.869	1.613	1.303	0.379	39.66	19287.04
7	1.848	1.611	1.297	0.377	39.66	19058.65
8	1.852	1.610	1.298	0.377	39.63	19091.85
9	1.843	1.609	1.296	0.377	39.59	18996.26
10	1.854	1.611	1.298	0.378	39.18	19133.44
11	1.864	1.618	1.301	0.379	39.27	19269.66
12	1.848	1.604	1.297	0.377	39.97	19016.01
13	1.858	1.614	1.301	0.378	39.99	19181.48
14	1.861	1.618	1.301	0.379	39.48	19241.01
15	1.871	1.617	1.304	0.379	39.67	19344.80
16	1.848	1.614	1.297	0.377	39.58	19072.84
17	1.858	1.619	1.300	0.379	39.72	19219.71
18	1.871	1.624	1.304	0.380	39.63	19385.39
19	1.871	1.628	1.301	0.380	38.00	19414.56
20	1.864	1.611	1.301	0.378	39.45	19230.96
21	1.853	1.611	1.298	0.378	39.49	19109.83
22	1.855	1.611	1.300	0.378	39.86	19127.58
23	1.853	1.610	1.298	0.378	39.50	19102.08
24	1.853	1.600	1.298	0.378	39.86	19044.54
25	1.871	1.618	1.304	0.380	39.42	19347.02
26	1.867	1.618	1.302	0.379	39.33	19306.22
27	1.857	1.611	1.299	0.378	39.33	19155.66
28	1.842	1.609	1.295	0.377	39.61	18985.03
29	1.859	1.615	1.301	0.379	39.92	19198.66
30	1.871	1.625	1.305	0.380	39.81	19384.11

According to the data from Table 4, the Multi-Objective Optimization did not found the only one solution. From the 30 solutions we can find out that t_1 is between 1.8 mm and 1.9 mm, t_2 is near 1.6 mm, t_3 is near 1.3mm. Since the plate thickness is accurate to 0.1mm in the most enterprises we chose two sets of values as optimal solution t_1 = 1.8 mm, t_2 = 1.6 mm, t_3 = 1.3 mm (First Series) and t_1 = 1.9 mm, t_2 = 1.6 mm, t_3 = 1.3 mm (Second Series) and used them as input in simulations with LS-DYNA. The results from simulations are summarizes in Table 5. Comparing the two series of optimal solutions, the second series the strain rate of the fuel tank is too high, so we choose the first series as the final optimal solution.

Table 5. Results from simulations of initial and optimized structures

Target value	Initial value	First series	Second series	Improvement Rate of First series
ε	0.4181	0.3751	0.4215	10.3%
E(J)	16578.2	18877.1	19322	13.8%
ΔL2(mm)	73	38.5	28	45.3%

The result of the optimization achieved desirable improvements. The elastic strain ε reduced by 10.3%, absorption of the energy E in area 1 increased by 13.8%, deformation ΔL2 of the rear suspension area 2 reduced by 45.3%. As showed in Figure 7, the deformation pattern of rear suspension area was obviously improved, which also improved the load capacity of this area, but also avoided the sharp objects created by over deformation the fuel tank, consequently, the safety of the rear impact has been improved.

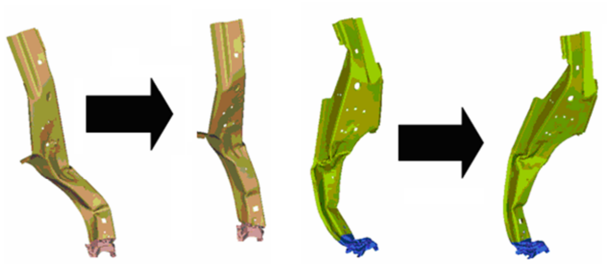

Figure 7. Deformation of car structure before and after optimization

4. Conclusions

From the current research, conclusion could be drawn that in rear impact it is evident and efficient to improve safety and crashworthiness by matching various thickness of main components. However, the weigh of the vehicle increased slightly, which dependent on two reasons as follow:

(1) The initial structure of the object vehicle is too weak,

(2) The number of the structures which we chose for optimization is limited.

The method used in the study provides a certain reference for optimization of components structure in rear impact.

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