Structural optimization of side impact bar

Wang Qian[1], *Yang Jikuang1 Guo Jie*[2]
(1. State Key Laboratory of Advanced Design and Manufacture for Vehicle Body, Hunan University, Chang sha,
2. Automobile Engineering Research Institute, Chery Automobile Co. Ltd)

Abstract: The aim of present study is to investigate improvement of crashworthiness of impact bar of door in side collision and to analyze the correlation of kinematics parameters and crashworthiness. We investigated the method how to perform optimization the structure. Based on the method of “response surface”, we optimized sectional parameters and thickness of impact bar using LS-DYNA and Hyper Study software. The results show that the time necessary to perform sub-structure model optimization using response surface method can be reduced to one fifth, comparing with traditional method using full scale model. We can conclude that the optimization method use in the study is more efficient than the traditional try and error way.
Keywords: impact bar, sub-structure model, optimization of structural parameter

1 Introduction

Compared with the frontal impact, in side impact the energy absorption ability of side part of vehicle is smaller. Moreover the space between the trim of door and the passengers is narrow. In the collision, the inner panel of the door will contact with the occupant directly. Therefore, improving the stiffness of the doors plays an important role in providing protection to the occupants during lateral collision [1]. The reduction of intrusion volume and speed is a key method to protect occupants in collision [2]. Therefore to improve and optimize the structure of side impact bar can improve the crashworthiness of the door [3].

The traditional simulation method using the finite element model of vehicle contains large quantity of elements and the computing time is long. A simplified sub-structure model can save computing time and reduce the time to develop a new vehicle. We used such model in optimization of the side impact bar, to find the optimal solution quickly.

Firstly we developed a vehicle collision finite element model and verified it, then extracted model of the impact bar to static simulations. Further we designed two other bars: hat-shaped and rectangular based on the above mentioned static simulation model, using the Hyperstudy and LS-DYNA software. Finally the optimal design method was selected and applied in optimization of the key structure parameters such as cross-section and thickness of the above-mentioned three different side bars. Also comparative analysis of crashworthiness of optimized bars was done.

2 Car side impact safety simulation and analysis

2.1 Vehicle finite element model validation

Previously developed model of the vehicle including the side impact bar [3] in LS-DYNA was selected to be used as input in current study. Unfortunately this side impact bar didn’t provide the occupant with acceptable level of safety. The whole model was already validated according requirements of FMVSS214. The validation was done to simulate a 120 ms of side barrier crash. As can be seen from Figure 1 in the collision process, B-pillar acceleration curves obtained from simulation compared to experimental one show some differences, but the overall trend is roughly the same. For the purpose of current study this validation was acceptable.

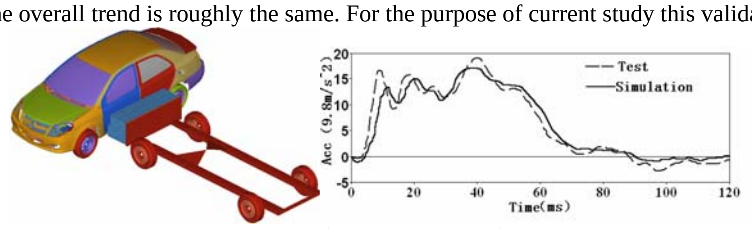

Figure 1. Validation curve of vehicle side impact finite element model

2.2 Elements of optimal design

In current study we decided to investigate the operational efficiency in the collision of the impact bar structures by FE simulations. From the finite element model of vehicle we extracted circular bumper sub-structure model to static simulations. The model is shown in Figure 2, it includes round bare, left and right end of the mounting bracket, and the central mounting brackets. The geometrical data of impact bar is as follows: radius R = 15.09 mm, thickness t_1 = 1.6 mm, thickness of left mounting bracket t_2 = 1.2 mm, thickness of right mounting bracket t_3 = 1.0 mm, thicknesses of middle mounting bracket t_4 and t_5= 1. 2 mm. Because the performance of the original bar was not acceptable and the previous study done at laboratory indicated that another geometry of the bar can be better, we decided to include in optimization two other bars with different geometry: hat-shaped cross-section and rectangular. To modify the geometry, MORPH command [4] was used. In order to make all types of cross-section impact bars comparable to resist the force, we adjusted appropriately the hat-shaped and rectangular impact bars

We optimized the above-mentioned two kinds of impact bars according to methodology of optimal design described in next chapter regarding the maximum strength and minimum mass, and the results were compared with these of the original circular impact bar. We cold find the optimal set of structural parameters that achieve the optimal design and for this set of parameters the reduction of intrusion was calculated in relation to the original circular bar.

In the optimization we used the crash set-up in accordance to regulation FMVSS-214b. The finite element model of impact bar for strength testing was developed. During computing the simulations, constraints for six degrees of freedom of the node space in the spot weld location of the impact bar were used. Meanwhile, in order to speed up the progress of computing, to save time of simulation and optimization, impact hammer in the vertical plane is loaded with the speed of 31.75 m/s [5].

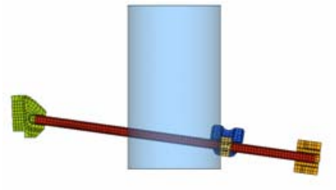
Figure 2. Circular impact bar

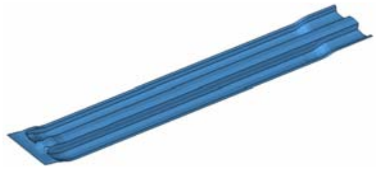
Figure 3. Hat-shaped impact bar

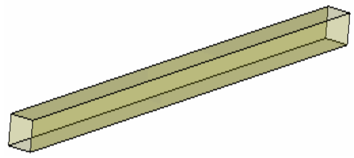
Figure 4. Rectangular impact bar

3 The basic theory of optimal design

Optimal design is using mathematical approximation. This procedure consists mainly of two aspects: one is how to select the sample points needed to construct a model, which belongs to design of experiments (DOE) area; second, constrict approximation model, which is the principal-agent model belonging to the mathematical approximation scope. The first aspect was solved by Latin square experimental design and full factorial experimental design by Hyperstudy software.

3.1 Experimental design method

3.1.1 Latin square experimental design method

With the Latin square experimental design method [6] we prepared the parameter set to Hyperstudy software. The Latin square experimental design method use k different levels of factors arranged in l columns this way that each one level in each row and each column appears usually once within the square, called the k × l Latin square. Locally control of rows and columns is carried out in both directions. It is the design space that each level is evenly divided (all the factors must have the same number of levels). Then, those levels are randomly combined to specify the design matrix used to define the n-point in the space.

3.1.2 Full factorial experimental design method

Full factorial design [7] is defined as a complete experiment, all the elements of the system for all levels of possible combinations are studied by an experimental design approach. By Full factorial experiment we can study factors (as geometrical parameters of the side impact bar), according to how strongly various factors are influencing the system response. At the same time, considering the certain factor we also can analyze the interaction between these factors influence on system response.

3.2 Response surface modeling

An optimization problem can be described as: to meet the given constraints, to select the appropriate design variable X, so that the objective function f (x) achieves optimum. Simplified mathematical model can be expressed as the following:

$$\left.\begin{array}{c} \min \text{ (or max) } f(x), \\ g_j(x) \quad (j=1,2,\cdots,m) \\ x_{iL} \le x_i \le x_{iU} \ (i=1,2,...n) \end{array}\right\} \tag{1}$$

where f(x) is the objective function, $g_j(x)$ is the constraint function, $x_{iL} \le x_i \le x_{iU}$ is the vector of design variables.

In the study the response surface methods [8] is used to construct the approximate model. Using this method we must first determine the form of the approximate function, and then, using statistical experimental design method in the design space, select a sufficient number of design points. Finally, by least square method construct the approximate model based on selected design points from the analysis results. The software HyperStudy supports the sequential response surface method to perform optimization. The objective function and constraints are approximated in terms of design variables using a second order polynomial:

$$\varphi_i(x) \approx A_{i0} + \sum_{j=1}^{m} A_{ij} x_j + \sum_{j=1}^{m} \sum_{k=1}^{m} A_{ijk} x_j x_k \tag{2}$$

where i ij, ijk A, A A 0 are the polynomial coefficients. To obtain response surfaces, you need to verify the surface level of the response. By analysis of variance parameters, using the coefficient of determination and adjusted coefficient we verify approximate function. The coefficient of determination (R^2) and adjusted coefficient of determination (R_{adj}) is defined as follows:

$$R^2 = \frac{\sum_{i=1}^{p} (\hat{y}_i - \bar{y}_i)^2}{\sum_{i=1}^{p} (y_i - \bar{y}_i)^2} \qquad R_{adj}^2 = 1 - \frac{\sum_{i=1}^{p} (y_i - \hat{y}_i)^2 (p-1)}{\sum_{i-1}^{p} (y_i - \bar{y}_i)^2 (p-k-1)} \tag{3) and (4}$$

In the above equations, P is the number of design point; k is the degree of freedom. When R^2 and R_{adj} is close to one the function accuracy is high and the predicted values from the function is close to values from the experimental data.

4 Optimization and analysis of impact bar structure

4.1 Description of the optimization problem

When the side door is crashed, the strong side impact bar can transfer and absorb the impact energy, and reduce the intrusion of this structure into the passenger compartment, so that it can reduce occupant injuries. Crashworthiness performance of the side impact bar affect the intrusion, intrusion speed and acceleration of the door, and other important kinetic parameters, so design of door side impact bar is the crucial in car body design.

The form and size of cross-section and thickness of impact bar are the important parameters that have influence on crashworthiness. Increasing thickness and radius of a circular impact bar can improve the crashworthiness performance, but it will increase car weight, and reduce fuel economy. Therefore in optimization of side impact bar we have consider minimization of the mass, while improving its resistance to intrusion force. The original impact bar resistance intrusion force was 64.5 kN. As the goal of optimization we decided to increase this force at least to 100 kN.

Based on mathematical expression described in chapter 2.2 the problem is as follows:

$$\left.\begin{array}{r}\text{Mass min}\\ F\ \text{max}\ \geqslant 100\text{KN}\end{array}\right\}$$

4.2 Optimization analysis

For the optimization of each shape of impact bar we used response surface models combined with experimental design (Deign of Experiment-DOE). We selected the appropriate design variables, and then used Hyperstudy software to extract the corresponding response surface model for optimization cycles. In the current paper the whole optimization procedure is showed for the case of circular impact bar only. However, the results are presented for all three types of bars.

4.2.1 Latin square experimental design and response surface modeling of circular impact bar

For original circular impact bar, we selected second-order response surface model as approximations model. We select the radius R and thickness t1 of impact bar, the thickness of the left and right side mounting brackets t2, and t3, the thickness of the middle bracket t4, t5 to run a 6-factors Latin square experimental design. Taking into account the computer time necessary for the simulations of side impact and in order to make the model more precise we select 49 test points as shown Table 1.

Table 1. Latin square experimental design of circular impact bar

Test NO.	R(mm)Rate	t_1 (mm)	t_2 (mm)	t_3 (mm)	t_4 (mm)	t_5 (mm)	F（KN）	Mass(kg)
1	-0.964663	2.084089	2.192984	1.309969	1.543847	1.320969	58.6954	1.467552
2	0.078344	1.882085	1.949586	2.040111	1.241604	1.879674	63.9696	1.830291
3	-0.786754	2.765709	1.474674	1.379388	2.470040	1.627181	93.4815	1.916353
4	-0.899693	1.870425	1.897842	1.706675	1.700128	1.716283	63.5556	1.421314
5	0.385130	1.512588	1.718566	1.014061	1.365557	2.383234	60.1098	1.591903
6	0.662138	2.829554	1.033847	1.526697	1.672398	1.189935	81.4411	2.734349
7	-0.937261	2.305128	2.489287	1.154867	2.392588	1.693103	90.4645	1.686734
8	-0.663216	1.691550	1.978251	1.462398	1.197370	1.806503	46.1018	1.369845
9	-0.511145	1.635691	1.201023	1.541112	1.514894	1.962970	57.5096	1.355210
10	-0.646709	2.447137	2.419969	1.327588	1.826112	2.444613	82.0189	1.885193
11	0.478683	2.711009	1.657181	1.629191	1.579579	1.475425	80.4308	2.599091
12	-0.060706	2.747944	2.441697	1.870372	2.212020	1.788458	105.7500	2.466276
13	0.559866	2.195166	1.108103	2.479576	1.168056	1.419471	63.4713	2.212944
14	-0.567541	2.585557	1.686513	2.316550	1.757788	2.174287	73.0155	1.998659
15	0.584138	1.666130	1.748758	1.802984	1.093251	1.300040	57.8727	1.799631
16	-0.594986	2.504069	1.372371	1.600040	1.585230	1.521257	61.3257	1.815774
17	0.705850	1.664297	1.012551	1.906148	1.989297	2.319191	86.6932	1.881105
18	-0.221334	2.175230	1.584191	1.575557	2.337054	2.118631	98.5961	1.917286
19	0.162233	1.547970	2.226550	1.761414	1.876148	1.267588	86.8618	1.674804
20	0.658785	2.332984	2.398464	1.235128	1.539471	1.936023	84.9855	2.448175
21	0.139178	2.292819	1.413458	1.214788	2.432975	2.010111	105.4930	2.131700
22	-0.531847	2.660997	1.498056	1.987551	2.011760	2.321604	69.9852	2.041144
23	0.146211	2.952371	1.179664	1.409894	1.054576	1.813464	69.9800	2.465108
24	-0.833886	2.434388	2.264788	1.749471	1.237703	2.484061	50.0860	1.744794
25	-0.301912	1.848251	1.433772	1.644699	1.112392	1.334586	51.2748	1.540623
26	-0.866496	2.086697	2.025997	2.330323	1.400323	1.013758	56.5421	1.560062
27	-0.247229	1.565111	1.239900	1.365750	2.063758	1.959664	78.9112	1.445112
28	-0.036840	2.782788	1.606950	1.778758	1.219345	1.464699	65.3438	2.314145
29	-0.464600	2.846604	1.822819	1.661604	2.276675	1.868566	94.1175	2.205989
30	-0.190987	2.993631	2.254554	2.276130	1.890997	1.500750	102.3100	2.521784
31	0.856735	2.637551	1.902054	1.734900	2.304061	2.041115	116.7940	2.875238
32	-0.173616	2.729200	2.166009	2.499013	1.134089	1.846364	64.1349	2.314467
33	-0.200449	2.256641	1.962137	1.143631	2.239935	1.019729	92.4387	1.945940
34	-0.334285	2.904935	2.097370	1.830709	2.104969	1.148999	103.8360	2.331183
35	-0.981241	2.135969	1.303761	2.139069	2.131950	1.685128	76.9591	1.523471
36	-0.103759	2.869894	1.090372	1.423234	1.708103	2.280166	89.8229	2.311558
37	-0.353511	2.802842	1.329297	1.333056	2.001513	2.485230	86.4361	2.162430
38	-0.376075	1.591112	2.094061	1.033464	1.479200	1.577788	58.0279	1.413481
39	0.306815	2.062975	2.179935	1.055425	1.783464	1.046169	79.9729	2.028913
40	0.324618	1.774867	2.376503	1.404200	1.281414	1.102551	59.7645	1.828110
41	0.886525	2.276523	1.553999	1.588761	2.447085	1.243251	119.3390	2.523658
42	-0.131515	2.527146	1.051148	1.821283	1.012842	2.187944	47.3475	2.036809
43	-0.845321	1.924658	1.728631	1.078251	1.305166	1.669579	47.3674	1.365761
44	-0.055666	2.002392	1.835323	1.994613	1.259729	2.271550	66.8950	1.849755
45	0.524075	2.016364	1.391130	2.012975	2.069388	2.059969	95.0896	2.140789
46	0.571277	2.961760	1.089013	1.027703	1.315691	2.257842	65.5974	2.741531
47	0.978748	1.908847	2.200040	2.032181	2.112137	1.075691	104.6320	2.313634
48	-0.964663	2.084089	1.277975	1.309969	1.543847	1.320969	58.6954	1.467552
49	0.078344	1.882085	1.884471	2.040111	1.241604	1.879674	63.9696	1.830291

From the objective optimization of circular impact bar, through the Latin-square test table we obtained force and mass, so finally objective function of the agent model could be constructed as follows:

$$F = -61.37 - 2.25R + 19.95t_1 + 6.37t_2 + 24.58t_3 + 36.04t_4 + 12.22t_5 - 4.1R^2 - 1.71t_1^{\,2} - 3.83t_2^{\,2} - 1.88t_3^{\,2} + 2.64t_4^{\,2} - 0.61t_5^{\,2}$$
$$+2.95Rt_1 - 0.89Rt_2 + 1.80Rt_3 + 4.47Rt_4 - 0.2Rt_5 + 5.63t_1t_2 - 5.07t_1t_3 - 2.01t_1t_4 - 5.07t_1t_5 + 1.34t_2t_3 - 1.42t_2t_4 + 1.18t_2t_5$$
$$+1.04t_3t_4 - 3.75t_3t_5 - 2.1t_4t_5 \qquad R^2 = 0.98, R_{adj} = 0.98$$

$$M = 0.003 + 0.67t_1 + 0.1t_2 + 0.08t_3 + 0.09t_4 + 0.03t_5 + 0.22Rt_1 + 0.002Rt_2 + 0.002Rt_3 \qquad R^2 = 0.984, R_{adj} = 0.978$$

The coefficient of determination (R^2) and adjusted coefficient of determination (R_{adj}) of the above function are close to 1, so the two functions are accurate. Based on the above agent model, the next step was the optimization process of this impact bar performed with Hyperstudy software. The result of this optimization is shown on Figure 5.

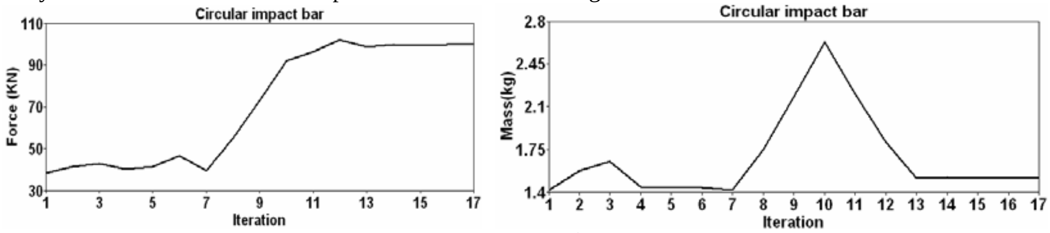

Figure 5. Optimization of circular impact bar

After 17 iterations，the functions of circular impact bar achieves convergence, there are three sets of data consistent with the constraints, in which 17th has minimum mass 1.5 kg, crash force of 99 kN. The reduction of the mass is 6.38%.

4.2.2 Full factorial experimental design and response surface modeling of hat-shaped impact bar

For the hat-shaped impact bar, we selected the second-order response surface model. Taking into account that thickness and height are affecting crashworthiness performance of this bar we selected height h and thickness t1 for full factorial experimental design. We selected 10 levels of each factor, constraints were set: 1mm <t1 <3mm, 18mm <h <32mm. Finally the following model was obtained:

$$F = -61 - 3.39h + 173t_1 - 0.26h^2 - 3.56{t_1}^2 + 1.97ht_1 \qquad R^2 = 0.99, R_{adj} = 0.99$$

$$M = -0.02 + 1.16t_1 + 0.01h^2 + 0.07ht_1 \qquad R^2 = 0.99, R_{adj} = 0.99$$

The coefficient of determination (R^2) and adjusted coefficient of determination (R_{adj}) of the above function are close to 1, so the two functions are accurate. Based on the above agent model, hat-shaped impact bar was optimized the same way as the circular one. The result of this optimization is shown on Figure 6.

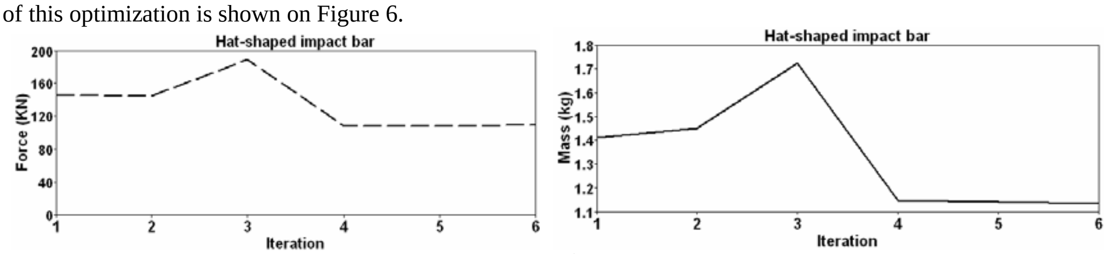

Figure 6. Optimization of hat-shaped impact bar

After 6 iterations，the functions of hat-shaped impact bar achieves convergence, there are six sets of data consistent with the constraints, in which 6th has minimum mass 1.14 kg, crash force of 108 kN. The reduction of the mass is 23.7%.

4.2.3 Latin square experimental design and response surface modeling of rectangular impact bar

For the rectangular impact bar, we selected the second-order response surface model. Taking into account that thickness, height and width are affecting crashworthiness performance of this bar we selected height *h* , width *w* and thickness t_1 for Latin square experimental design. The set of constraints was: 14 mm <*w* <26 mm, 18 mm <*h* <32 mm ,1 mm< t_1 <3 mm. Finally we obtained the following model:

$$F = 111.25 - 12.8w - 19.1h - 22.6t_1 - 15.44w^2 + 0.84h^2 + 5.53{t_1}^2 - 9.03wh + 2.76wt_1 + 3.58ht_1 \qquad R^2 = 0.91 \qquad R_{adj} = 0.91$$

$$M = 0.31 + 0.63t_1 + 0.07wt_1 + 0.06ht_1 \qquad R^2 = 0.98 \qquad R_{adj} = 0.98$$

The coefficient of determination (R^2) and adjusted coefficient of determination (R_{adj}) of the above function are close to 1, so the two functions are accurate. Based on the above agent model, rectangular impact bar was optimized the same way as the circular one. The result of this optimization is shown on Figure 7.

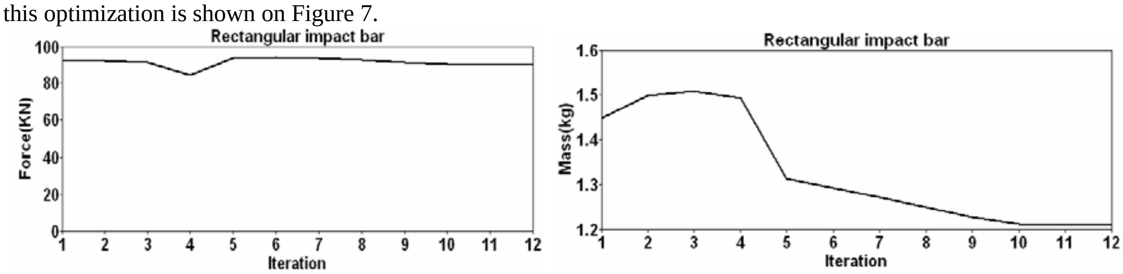

Figure 7 Optimization of rectangular impact bar

After 12 iterations，the functions of rectangular impact bar achieves convergence, there are three sets of data consistent with the constraints, in which 12th has minimum mass 1.2 kg, crash force of 90 kN. The reduction of the mass is 17.2%.

The result from all optimizations showed that hat-shaped impact bar with height 23.53 mm, the thickness: 1 mm, has a best mass force performance that means it has the best crashworthiness and minimal weight.

5 Conclusions

By combining response surface method and FE-simulation, we optimized the structural parameters side impact bar considering crashworthiness and mass relation. The optimization method used in the current study can solve highly nonlinear problems. So this method can be used in automotive concept design phase and structural optimization phase for improvement of crashworthiness and mass performance of vehicle structure, saving computing time and production costs.

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