Optimization of the Structure of Crash-Box Based on RCAR Front Impact Test

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Abstract: The current paper dealt with optimization of crash box in front impact based on procedure used by Research Council for Automobile Repairs (RCAR). Firstly, the parameters of the structure of the crash-box were selected. Then Orthogonal Arrays design of experiments was used to generate the test sample points. A global optimization of the structure was preformed based on the Kriging approximation model. The optimized crash-box can absorb sufficient energy. The section force at crash-box was decreased to achieve the design standard. The optimized crash-box matches well with the front rail and can effectively protect the main front parts of vehicle in front collisions at low speed.

Keywords: RCAR test; crash-box; kriging model; optimization; matching

1. Introduction

There are several standards to define the speed of low speed impact in various countries. Generally the speed below 15 km/h is considered as low. This type of impact is very common in urban traffic. So we decide to design a device between crash-box and front rail to protect the main parts of the car at low speed impact because it is important to reduce the repairing cost.

Sohn et al. [1] did some research on the energy that hydraulic forming bumper bracket absorbed in the impact. The result showed that this bracket was better than the traditional one, but the cost of production was quite high that only applicable for the luxurious car. Redhe[2] optimized the shape of a vehicle crash-box using LS-OPT. The performance of the car was good in the low speed impact after optimization. The mass of the car was also cut down. Hilmann et al. [3] analyzed the crashworthiness of the bumper system using Genetic Algorithm (GA). This method was applied to design the body in white.

Many people have done research on the low-speed impact in China [4, 5], but a little research using test procedure of the Research Council for Automobile Repairs (**RCAR**) was done. Xianling et al. [6] introduced the requirement of the RCAR test. They used a finite element （FE） model of a passenger car from Greatwall Automobile. Collision energy calculation and spring element were analyzed to illustrate the optimization of the energy absorbed structure. The section force of crash-box was reduced. The crash-box matched the front rail well. Yongsheng Y [7] simplified the whole car to a sled model. He improved the structure of the crash-box according experience. However, he did not consider if the crash-box matched the front rail.

In the current study the authors simplified a whole car to a sled model. An Orthogonal Arrays experiment was designed to get sample points. A mathematical model was built based on the Kriging approximation model. The result of FE model verified the approximation surrogate model. The structure of crash-box was optimized using Adaptive Simulated Annealing and the global optimal parameters were got. At the same time we tried to have a good matching of the crash-box to the front rail.

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2. Method and Material

2.1. Rigid Wall Sled Test and Simulation Model Description

To study the real response of existing structure and to evaluate the FE model of this structure attached to the sled in configuration as shown in Fig.1 we conducted, a rigid wall sled test with full overlap at impact velocity of 40 km/h was designed at State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body in Hunan University. The mass of the sled was 1020 kg. In front end of sled, symmetrically about the centerline, four thin-walled tubes were mounted to absorb crash energy and protect the sled. The length of each tube was 105 mm. Length of front rail was 336 mm and the length of the crash-box 147 mm. A full-scaled FE model for the optimization was built according to this real sled (Figure 2), which includes 22714 nodes and 21800 elements. The material property of front rail and thin-walled tubes was set based on one of real material. In order to save computing time, the rear parts of the sled body were regarded as rigid. The validity evaluation of rigid wall impact FE model was focus on deformation of front rail and acceleration of vehicle center of gravity.

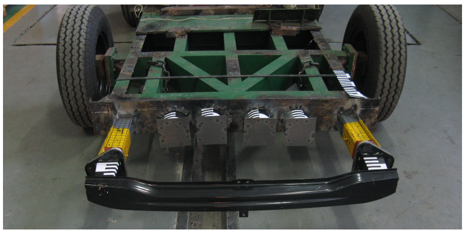

Figure 1. Sled test

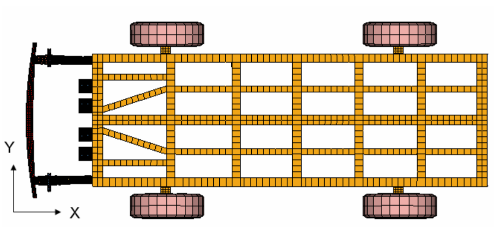

Figure 2. Finite element model

2.2. Calculated Model Based on the RCAR Test

The optimization of the crash-box was performed in the configuration according to RCAR test protocol [8]. This configuration is the 40% offset (U) impact test with rigid wall at speed of 15^{+1}_{-0} km/h. As shown in Fig.3, the angle (**A**) between front edge of fixed obstacle and the direction perpendicular to the speed vector of vehicle is 10. The radius (**R**) of corner is 150 mm. In the optimization procedure, the validated FE sled was used as shown in Fig. 4.

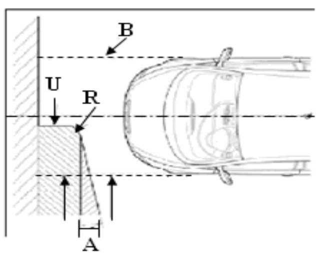

Figure 3. Descriptions of RCAR test

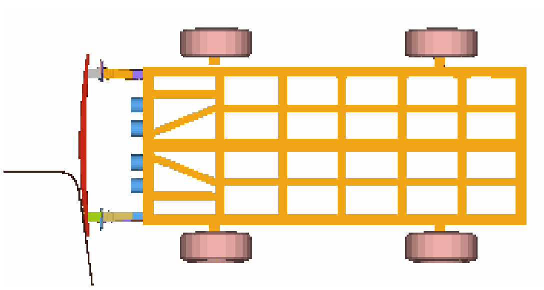

Figure 4. FE model RCAR test

2.3. Objective Function Definition

When the car is tested according to the RCAR procedure, the crash-box at the impact side deforms and absorbs the most energy, while the bumper and the crash-box on the other side absorb a little. Therefore in the current study we decided is to optimize one crash-box that is on impact side.

The energy absorbed by the crash-box (**E**) can be expressed:

$$E=\int_0^s F(s)\,ds \qquad (1)$$

where: F(s)—section force; s—deformation of the crash-box. For the certain deformation, this force of the crash-box becomes high as the energy absorbed increases. The front rail and other main parts of the car could be damaged when this force rich a certain value. So we try to reduce its peak value and increase the average level. The original front rail collapsed, when the section force was at the level of 120 kN. The crash-box should protect front rail in the low speed impact. We designed that the crash-box should be crushed step by step. The first peak value of section force shouldn't be more than 85 kN and the second no more than 90 kN.

As the optimization objective we selected the maximum amount of absorbed energy by crash-box. The section force peak values are the boundary constraints. Therefore, the optimization problem can be described as follows:

$$\text{Max}\ (\mathbf{E}); \quad \mathbf{F_1} \le 85; \quad \mathbf{F_2} \le 90; \qquad (2)$$

where: **E** is energy the crash-box absorbed in J. $\mathbf{F_1}$ and $\mathbf{F_2}$ are values of two peak of the section force in kN.

2.4. Design of Experiment

It is presented in Fig. 5 that front bumper, crash-box, flanges and front rail are connected rigidly. The key parameters in current optimization of crash-box include the size of the front crash-box (**a**), triggers width (**b**), trigger depth(**c**) and thickness of the crash-box (**t**). The set of parameters of crash-box and its boundary are shown in Table 1. In the selection of boundaries of crash box, we considered constrains by bumper and front rail.

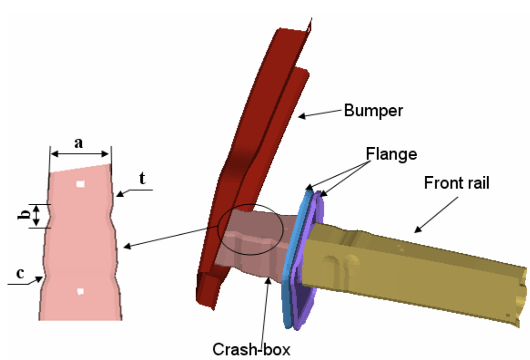

Figure 5. Key parameters of crash-box

Table 1. Parameter identification

Parameter	Description of the parameter	Current value	Lower boundary	Upper boundary
a [mm]	Size of the front crash-box	60	60	120
b [mm]	Triggers width	25	20	35
c [mm]	Trigger depth	4	2	5
t [mm]	Thickness of the crash-box	1.5	1.2	1.8

In order to obtain adequate samples, and then make it easy to establish mathematical model, in the present study the $L_{16}(4^4)$ orthogonal experiment design was chosen as shown in Table 2. For the selected **a, b, c** and **t**, we calculated **E, F_1** and **F_2** from DYNA simulations.

2.5. Surrogate Model Construction

For many real world problems, a single simulation can take many minutes, hours, or even days to complete. Constructing approximation models is one way to alleviate this problem. The approximation models mimic the behavior of the simulation model as closely as possible and at the same time make computing short. Surrogate models are constructed based on modeling the response of the simulator to a limited number of intelligently chosen data points [9]. The usual methods to construct approximation models are Response Surface Model, Kriging Model, Taylor Series Approximation and Variable Complexly Model.

In the study we used the theory of kriging that was developed by the French mathematician Georges Matheron based on the Master's thesis of Daniel Gerhardus Krige in 1951. It is an estimated minimum variance unbiased estimator model. The Kriging model expresses the unknown function $y(x)$ as:

$$y(x) = f(x) + z(x) \tag{3}$$

where: $f(x)$ is the known approximation function, and $z(x)$ is the realization of a stochastic process with mean zero, variance σ^2, and nonzero covariance. Compared with other models, Kriging model can cover all sample points. The quality of the approximate surface is good. This was the main reason of our selection to use the Kriging model to construct approximate surface.

Table 2. The design samples

Sequence number	**a** [mm]	**b** [mm]	**c** [mm]	**t** [mm]	**E** [J]	**F_1** [kN]	**F_2** [kN]
1	60	20	2	1.2	4831	66.87	88.18
2	60	25	3	1.5	5806	117.00	104.32
3	60	30	4	1.6	5838	94.66	93.92
4	60	35	5	1.8	6200	113.77	87.73
5	86	30	3	1.2	4609	59.41	75.42
6	86	35	2	1.5	5106	90.22	87.80
7	86	20	5	1.6	5864	81.49	91.58
8	86	25	4	1.8	4968	102.08	99.13
9	110	35	4	1.2	4929	62.57	73.73
10	110	30	5	1.5	5720	88.62	96.94
11	110	25	2	1.6	6048	112.89	79.80
12	110	20	3	1.8	4556	124.92	74.62
13	120	25	5	1.2	5157	54.51	93.66
14	120	20	4	1.5	5453	90.23	81.61
15	120	35	3	1.6	932	102.97	95.87
16	120	30	2	1.8	5082	126.85	112.86

2.6. Adaptive Simulated Annealing Algorithm

To calculate the surface of Kriging Model we used Adaptive simulated annealing (ASA) algorithm that is based on Simulated Annealing (SA). SA [10] is a generic method for the global optimization problem of applied mathematics, namely locating a good approximation to the global optimum of a given function in a large search space. The method was independently described by Scott Kirkpatrick, C. Daniel Gelatt and Mario P. Vecchi in 1983. The name and inspiration come from annealing in metallurgy, a technique involving heating and controlled cooling of a material to increase the size of its crystals and reduce their defects. The heat causes the atoms to become unstuck from their initial positions and wander randomly through states of higher energy; the slow cooling gives them more chances of finding configurations with lower internal energy than the initial one.

ASA is a variant of SA algorithm in which the algorithm parameters that control temperature schedule and random step selection are automatically adjusted according to algorithm progress. This makes the algorithm more efficient, intelligent and less sensitive to user defined parameters than canonical SA.

3. Results

3.1. Rigid wall FE Model Validation

Comparison of front rail deformation in test and simulation presented in Fig.6, We can see that the deformation pattern of the front rail and its model is similar. Also the time duration, shape of acceleration curves and corresponding peaks values are similar (Fig.7).

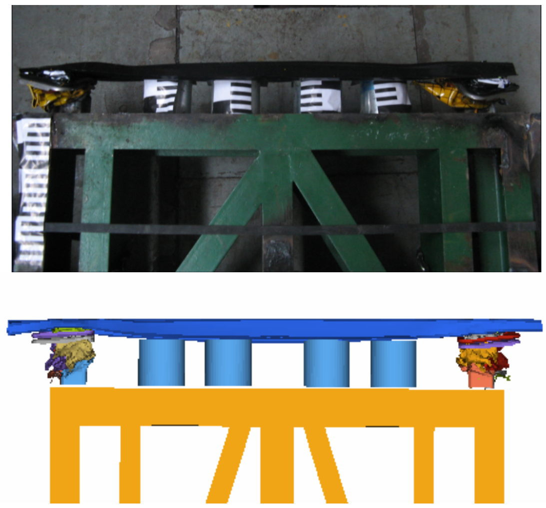

Figure 6. Comparison of front rail deformation in test and simulation

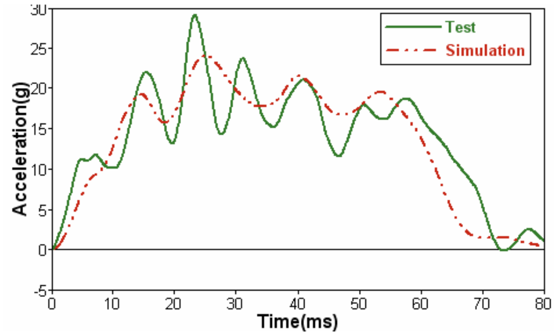

Figure 7. Acceleration curves of sled vehicle in test and simulation

3.2. Validity Evaluation of Approximation Surrogate Model

The authors constructed Kriging model using the sample points as shown in Table 2. The verification of the approximation surrogate model by LS_DYNA simulations performed with some other sample points is presented in Table 3.

Table 3 shows, the errors between the results of surrogate models and the ones of FE models are below 10%. So it is considered that the approximate surrogate model mimics the model of RCAR test well.

3.3. Analysis of Optimization Result

From the calculation with surrogate model, we got the best objective with the set of values of optimized parameters, as shown in Table 4.

Using this set of values of the parameters by the FE model of offset cash we compared the results of approximation surrogate model and ones of the FE model as is presented in Table 5. This table shows also that the errors between the result of surrogate models and the ones of FE models are below 10%.

The comparison of section force of the crash-box before optimization and after is shown in Fig.8. The crash-box absorbing energy and peak of section force before optimization and after is shown in Table 6.

Table 3. Results of verification of the approximation surrogate model

Parameter				Compare of results								
				Results of surrogate model			Results of FE model			Error [%]		
a [mm]	**b** [mm]	**c** [mm]	**t** [mm]	**E** [J]	F_1 [kN]	F_2 [kN]	**E** [J]	F_1 [kN]	F_2 [kN]	**E** [J]	F_1 [kN]	F_2 [kN]
73	30	4	1.6	6000	87.4	101.8	5784	93.3	96.3	3.7	5.7	6.3
86	20	3	1.5	5637	73.8	89.8	5815	80.5	90.2	3.1	8.3	0.4
99	25	3	1.5	5481	77.8	96.5	5886	80.0	103.5	6.9	2.8	6.8

Table 4. Best objectives and optimized parameters

Parameter	**a** [mm]	**b** [mm]	**c** [mm]	**t** [mm]	**E** [J]	F_1 [kN]	F_2 [kN]
value	86.2	27.2	3.7	1.5	6352	77.6	89.9

Table 5. The results of approximate model compared with the results of finite element model

Optimization objectives	Surrogate model results	FE model results	Error [%]
E [J]	6352	5871	8.2
$\mathbf{F_1}$ [kN]	77.6	83	6.5
$\mathbf{F_2}$ [kN]	89.9	87.5	2.7

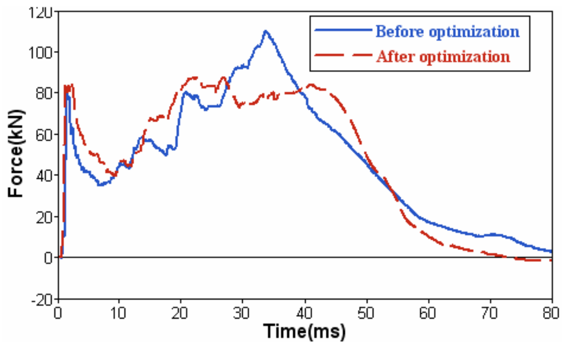

Figure 8. Section force of crash-box after optimization

Table 6. Comparison of the indicators improved

Optimization objectives	Before optimization	After optimization
E [J]	5905	5871
$\mathbf{F_1}$ [kN]	82.4	83.0
$\mathbf{F_2}$ [kN]	109.3	87.5

Figure 8 and Table 6 shows that crash-box can absorb energy sufficiently in low speed impact. The first peak's value of section forces is still below 85 kN. The second peak's value of section forces is below the target of 90 kN. Therefore the crash-box and the front rail can match well in impact. The section force in the low speed impact is reduced in optimized crash-box and it can protect front rail and other parts to be damaged in low speed impacts.

4. Discussions

The structure of crash-box is optimized based on RCAR test council, while performances in other test are not validated. And the influence of material properties was not considered. The peak value section force of front rail is low. So we could reinforce the structure of the beam and increase its stiffness. We will have more space to optimize crash-box. In the further study we will try to consider those factors in optimization.

5. Conclusions

The authors optimized the structure of crash-box using Kriging model based on RCAR test. It is shown that the accuracy of the surrogate model based on Kriging Model is high by comparing the result between surrogate and FE model. The section force of crash-box optimized meets the design standards. The crash-box can match the front rail batter in the impact. The crash-box can be crushed completely to absorb the impact energy and protect the front rail and other parts.

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