Crashworthiness Optimization Design of Minibus Structure

Tianli Ling¹, *, Zheng Yu²

¹Zhejiang University. Zhejiang University/University of Illinois at Urbana-Champaign Institute, ZJU-UIUC Institute, Haining, China
²University of Connecticut, School of engineering, Connecticut, Storrs, USA

*Corresponding author: Tianli.18@intl.zju.edu.cn

Abstract. This paper built the 100% frontal crash model of the minibus, 8 thickness of the components which have obvious effect on vehicle crash performance were selected as design variables, and choose the appropriate evaluation index as the responses. Use DOE experimental design method to get 70 set training data and built Kriging approximate model based on the training data. The approximate model is optimized by PSO algorithm, in the optimized scheme, the $a_{max}$ and $m$ has decreased by 7.6% and 0.87%, $D1$, $D2$ and $D3$ has decreased by 7.7%, 3.1% and 5.3%.

Keywords: 100% frontal crash, DOE, Kriging approximate model, PSO algorithm

1. Introduction

The research on automobile crash safety in foreign countries started earlier, and the research methods and systems are more mature than those in China. In order to ensure the passive safety performance of the vehicle, many foreign experts and technicians have carried out a lot of analysis and research on the collision of the front and side of the vehicle. The main aspects include the use of materials, and the improvement of structure and technology.

In the aspect of simulation test, with the wide application of finite element technology in the 1980s, computer simulation began to step into the stage of research and analysis. In 1985, French researchers first completed the crash simulation analysis of the whole vehicle and verified it through the sled test. The verification results showed that the finite element simulation results were consistent with the results of the sled test, which promoted the rapid development of finite element method analysis in the field of automobile collision [1]. With the continuous development of CAE simulation technology, software simulation is more and more in line with the actual conditions, commonly used software Hyperworks, LS-DYNA, NASTRAN and so on [2].

In the aspect of body material technology, foreign researchers have not only done in-depth research on traditional metal materials, but also explored new materials such as foaming and sandwich. A.G.Mamalis carried out crushing tests and simulation analysis on hollow square pipes, aluminum foam, polyurethane and pipe fittings reinforced with foaming materials in the middle, and evaluated their crashworthiness through energy absorption ratio in three aspects: volume, energy, and cost [3].Aachen in Germany and Ulsan University in South Korea introduced plastic fender and fender to the side panel application of a new energy vehicle, and carried out theoretical and experimental research on its forming and assembly process [4].
In terms of energy absorption structure, Ford Company in the United States has designed a variable cross section type of energy absorption box with ultra-high strength steel. After crashworthiness testing, the results show that the new type of energy absorption box has better crashworthiness compared with the traditional energy absorption box [5]. KVA developed a MSS front beam, and put it on the test vehicle, which was verified by the crash test.

2. Minibus frontal 100% crash analysis

2.1. Finite element model

Because the vehicle finite element model is very large and complex, it is necessary to simplify the model in the simulation analysis, which can save the computer's working time and improve the efficiency. In this paper, some non-bearing parts of the minibus body, the small rounded corners and edges between the two surfaces are ignored, because the neglect of these parts will not cause substantial impact on the simulation results. Similarly, some parts that have very slight influence on the mechanical structure, such as stamping bars and holes, will also be ignored or simplified. However, the important parts of the body should be consistent with the original CATIA model as much as possible [6], which can play the role of simplifying the model and restore the characteristics of the collision model in a good way. Some parts, such as the engine, transmission, etc., whose stiffness is much greater than the thin-walled sheet metal parts, and whose deformation is minimal even when subjected to large impact forces during the whole collision process, are defined as rigid bodies.

The finite element model of 100% frontal overlapping deformable barrier collision of the minibus, including rigid barrier wall, body, chassis, tires, etc., which is shown in the Fig.1. The total number of units is 492151, with triangle units accounting for 4.7% and less than 5%. According to the requirements of C-NCAP regulations, the vehicle under test collided vertically with the fixed barrier wall surface at a speed of 56km/h. In this simulation, the impact contact mode is rigid wall, the impact speed is 56km/h (along the positive direction of the X axis), and the impact Angle is 100%. Frontal impact means that the normal direction of the barrier wall is parallel to the driving route of the minibus. At the same time, in order to make the simulation results more realistic, the vehicle model is applied with the gravity acceleration of vertical downward.

![Figure 1. Finite element model of 100% frontal collision of minivan](image)

2.2. Analysis of 100% Frontal Crash of Minibus

The pre-processing is completed in Hyperworks, and the generated K file is submitted to LS-DYNA for calculation.
3. Kriging approximate model

3.1. Design variables
In the study of automobile frontal collision, the study area can be divided into three parts. The first part is the front energy absorption area, which may have large crushing deformation in the collision process, and mainly assumes the role of energy absorption and shock absorption at the early stage of the collision. The larger the deformation is, the more energy absorption and shock absorption will be, including the bonnet, bumper and the buffer area on the bumper. The second part is the body longitudinal inner and outer plates, left and right subplates and other structures. This part of the area can further absorb the energy generated by the collision in the process of collision and play the effect of cushioning and shock absorption. The research significance of this part is the greatest. The third part is the cockpit. The structural strength of the cockpit is very high, in order to resist deformation and protect the safety of the occupants. In the research on the main energy absorbing components of automobile frontal collision, the energy absorbing ratio of the front rail is about 25%, the energy absorbing box is about 8%, and the energy absorbing ratio of the front beam is slightly lower than the first two, but also reaches about 5%. Therefore, these key parts should be taken into consideration in the optimization design process of 100% frontal collision. In this paper, according to the C-NCAP new car evaluation index, the front part of the car body should be crushed and fully deformed in the collision process, which can absorb a lot of collision kinetic energy and effectively reduce the peak acceleration at the lower end of B-pillar. In order to meet this principle, the thickness of 8 sheets on the front of the car body is selected as the design variable after comprehensive consideration (shown in Fig.3)

3.2. Objective functions
In the evaluation index of automobile frontal crash test, the impact performance of the vehicle is generally considered from several points, such as energy absorption, body acceleration, invasion of
key points and impact time. Because the lower end of the body B-pillar has a large stiffness and is not easy to deform in the collision process, the acceleration at this point is chosen to represent the acceleration of the whole vehicle. According to engineering experience and C-NCAP rules, and considering the damage caused by body deformation to passengers’ chest, head, feet and other parts, this paper selects the pipe beam of instrument panel, the hole of steering column of front coaming and the clutch pedal of lower front coaming as the reference point of the intrusion amount. In addition, considering the mass m is an important index of lightweight, so this article selects the response for the B column bottom $a_{\text{max}}$ peak acceleration, the mass m, dashboard illustrated the amount back into D1, dash panel on steering column hole back into the amount in D2 and the dash panel clutch pedal backwards into the amount D3 as research response.

3.3. DOE and training samples

After determining the design variables and responses, a certain amount of training data should be obtained for the subsequent establishment of the approximate model. In consideration of the influence on the accuracy of the approximate model and the computing power of the computer, this paper uses Latin hypercube test to obtain 70 sets of training data. The training data is based on the initial value of the design variables, and the change of each variable is controlled within a certain range during the design test. After obtaining the test data of the design variables, each group of data is separately brought into the original finite element model to get the modified model, and the calculation is submitted. Finally, 70 groups of training data will be obtained. The computer used for calculation in this paper is 8-core CPU, 4G operating memory, and the acquisition time of a single group of training data is about 20 hours. The obtained training data are shown in Table 1.

**Table 1. Design variable test design table**

| t1  | t2  | t3  | t4  | t5  | t6  | t7  | t8  |
|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.66| 1.39| 1.84| 0.69| 1.13| 1.05| 1.51| 1.46|
| 0.68| 1.41| 0.99| 1.14| 0.92| 0.81| 1.44| 1.1 |
| 0.72| 1.2 | 1.47| 1.17| 1.73| 0.77| 1.41| 1.25|
| 0.73| 1.03| 1.54| 1.54| 1.43| 1.35| 1.92| 0.86|
| 0.76| 1.13| 1.77| 0.8 | 1.06| 1.09| 0.77| 1.71|
| 0.77| 1.51| 1.74| 1.67| 1.24| 1.39| 1.07| 1.88|
| 0.79| 1.05| 0.88| 1.62| 1.78| 1.92| 1.89| 0.87|
| 0.84| 1.29| 1.76| 1.24| 1.2 | 0.72| 0.99| 1.5 |
| 0.94| 1.78| 0.79| 1.21| 1.65| 1.65| 1.5 | 1.35|
| 0.95| 0.91| 1.25| 0.92| 0.86| 1.84| 1.2 | 0.75|
| 0.96| 0.81| 1.48| 1.97| 0.98| 0.75| 0.8 | 1.16|
| 0.98| 1.02| 1.36| 1.63| 0.73| 1.71| 1.88| 1.51|
| 1.31| 0.87| 1.11| 0.75| 1.92| 0.91| 1.61| 1.33|
| 1.33| 1.52| 1.01| 1.1 | 0.8 | 1.28| 1.63| 0.95|
| 1.37| 1.25| 0.81| 1.58| 1.22| 0.65| 0.95| 0.88|
| 1.39| 1.01| 1.37| 0.79| 0.77| 1.79| 0.84| 1.99|
| ... | ... | ... | ... | ... | ... | ... | ... |
| 1.96| 0.94| 1.22| 0.66| 1.48| 1.86| 1.82| 0.69|
| 1.97| 0.86| 1.99| 1.07| 1.91| 1.02| 0.66| 1.29|
| 2 | 1.17 | 0.68 | 2 | 1.52 | 1.81 | 0.75 | 1.89 |
Table 2. Objectives

| $a_{max}$ | $m$  | $D1$ | $D2$ | $D3$ |
|-----------|------|------|------|------|
| 54.8      | 717.5| 86.5 | 240  | 230  |
| 52.9      | 716.9| 84.5 | 209.5| 210  |
| 55.3      | 717.7| 92.1 | 246.2| 237.7|
| 52.9      | 718  | 92.1 | 246  | 252.1|
| 54.6      | 716.7| 85.9 | 243.1| 238.9|
| 55.3      | 717.4| 89.5 | 244.6| 256.8|
| 53.9      | 718.3| 102.8| 286.6| 276.4|
| 55.1      | 716.9| 86.1 | 222  | 224.5|
| 54.7      | 717.9| 97.8 | 264.8| 256.7|
| 56.9      | 716.6| 82.1 | 220.6| 229.5|
| 55.1      | 716.3| 79.1 | 212.5| 197.7|
| 58.6      | 717.8| 53   | 194.4| 217.5|
| 56.3      | 718.2| 94.4 | 255.5| 262.6|
| 57.3      | 717.2| 84   | 200.3| 224.9|
| 57.1      | 716.6| 85   | 232.3| 233.2|
| 55.3      | 716.8| 79.3 | 207.6| 229.5|
| ...       | ...  | ...  | ...  | ...  |
| 53.8      | 718.1| 98.2 | 255.2| 251.7|
| 56.3      | 717.2| 74.1 | 263.9| 267.5|
| 46.5      | 717.4| 96.5 | 261.8| 262  |

3.4. Kriging approximate model

Based on the obtained training data, this paper establishes the Kriging approximate model to replace the original finite element model to carry out the following optimization design. When the approximate model is established, it is necessary to evaluate the accuracy of the approximate model. Only when the accuracy of the approximate model meets the expected requirements, the approximate model can effectively restore the finite element model. The three-dimensional diagram of the Kriging approximate model established in this paper is shown in Fig.4.

![Figure 4. Kriging approximate model](image)

The accuracy of model can be evaluated by RAAE and $R^2$, they can be calculated by Equation 1 and 2:

$$RAAE = \frac{1}{n} \sum_{i=1}^{n} \frac{|y_i - \hat{y}_i|}{|y_i|}$$  \hspace{1cm} (1)
The results are shown in Table 3.

### Table 3. Objectives

| Objectives | RAEE   | R2   |
|------------|--------|------|
| $a_{\text{max}}$ | 0.08   | 0.86 |
| $D1$       | 0.08   | 0.85 |
| $D2$       | 0.05   | 0.92 |
| $D3$       | 0.06   | 0.90 |
| $m$        | 0.05   | 0.94 |

As can be seen from Table 3, the average relative error and determination coefficient of each response value of the 100% frontal overlapping collision Kriging approximate model meet the requirements, and it is still within the acceptable range under strong nonlinear conditions with high accuracy. Therefore, it can well replace the finite element model of the mini bus collision for subsequent optimization design.

### 4. Particle Swarm Optimization

Particle Swarm Optimization is widely used optimization algorithm. In 1995, a group of researchers led by Kennedy and Eberhar developed a new calculation method to study the predation behavior of birds. This method simulates the predation behavior of birds with the iterative change of particles, and searches the optimal particles in the spatial solution set with a certain number of particles as the target. Compared with the traditional genetic algorithm, particle swarm optimization eliminates the operation of crossover and mutation, and the operation is simple and easy to implement. The PSO algorithm follows the principles of evolutionary substitution calculation: (1) Initialization starts from a group of random populations; (2) The way to search for the optimal solution is to update the population continuously; (3) The evolution of the next generation depends on the particle population of the previous generation.

The general calculation process of particle swarm optimization algorithm is as follows:

1. Initialize a group of particles (suppose the size of the population is m particles), and the initialization content includes random information of particles (including position, velocity and direction);
2. Evaluate the fitness of each particle;
3. Evaluate each particle in the space and compare its current fitness with the optimal position Pbest it experienced in the last search process. If the fitness is better than the previous optimal position Pbest, it will replace the previous Pbest to become the current optimal position;
4. Then re-evaluate each particle in the space and compare the fitness of each particle with the GBest of the optimal position experienced in the whole search space in the last round. If the fitness is better than the GBest of the optimal position in the last round of global search, it will replace the previous GBest to become the new round of global optimal position;
5. Variate the velocity and position of the particle according to equations (1) and (2);
6. If the condition for the end of the search behavior is not met (that is, the fitness meets the specified requirements or meets the preset maximum algebra), then go back to Step 2 to reevaluate the fitness of the particle.

Particle Swarm Optimization (PSO) is used to optimize the approximate model deterministically. In this paper, eight plate thicknesses, which have great influence on 100% frontal impact of minivan,
are determined as design variables, and the peak acceleration at the lower end of B-pillar, the vehicle mass and the invasion amount of key parts are taken as responses. Based on the training data obtained from DOE test, a Kriging approximate model is established. According to the established approximate model, the multi-objective optimization design is carried out. In the multi-objective optimization design, the peak acceleration at the lower end of B-pillar and the intrusion at key parts should be minimized as far as possible, and the vehicle mass should also be reduced. The mathematical model of the deterministic multi-objective design is expressed as follows.

\[
\begin{align*}
\min a_{\text{max}}(t_1, t_2, t_3, \ldots, t_{10}) \\
\min m(t_1, t_2, t_3, \ldots, t_{10}) \\
D_1(t_1, t_2, t_3, \ldots, t_{10}) \leq 97.6 \text{mm} \\
D_2(t_1, t_2, t_3, \ldots, t_{10}) \leq 260 \text{mm} \\
D_3(t_1, t_2, t_3, \ldots, t_{10}) \leq 268.4 \text{mm} \\
t_1, t_2, t_3, \ldots, t_{10} \in [1.1, 1.25, 1.1, 1.1, 1.65, 1.63, 0.89, 0.7] 
\end{align*}
\]

(3)

Where, the inertia weight of particle swarm optimization algorithm is 0.9, and the acceleration constant is \(c_1 = c_2 = 1.4\); The step size of the optimization algorithm is 0.5, the number of iterations is 2000, and the number of particles is 10. After the optimization design of the approximate model, the deterministic optimization scheme 1 is obtained. The results are shown in Table 4.

| Objectives | Base model | Optimized model |
|------------|------------|----------------|
| T1         | 1.1 mm     | 1.2 mm         |
| T2         | 1.25 mm    | 1 mm           |
| T3         | 1.1 mm     | 1.3 mm         |
| T4         | 1.1 mm     | 0.9 mm         |
| T5         | 1.65 mm    | 1.1 mm         |
| T6         | 1.63 mm    | 1.3 mm         |
| T7         | 0.89 mm    | 0.92 mm        |
| T8         | 0.7 mm     | 0.51 mm        |
| \(a_{\text{max}}\) | 57.6 m/s\(^2\) | 53.2 m/s\(^2\) |
| D1         | 97.6 mm    | 90.1 mm        |
| D2         | 260.6 mm   | 252.4 mm       |
| D3         | 268.4 mm   | 254.3 mm       |
| \(m\)      | 716.85 kg  | 710.61 kg      |

It can be seen from Table 4 that, after the deterministic optimization of the approximate model by using the particle swarm optimization algorithm, the peak acceleration at the lower end of pillar B decreases from \(57.6 \text{ m/s}^2\) to \(53.2 \text{ m/s}^2\). The backward intrusion at the tube beam of the instrument panel D1 decreases from 97.6 mm to 90.1 mm, the backward intrusion at the steering column hole of the front coaming D2 decreases from 260.6 mm to 252.4 mm, and the backward intrusion at the clutch pedal of the lower front coaming D3 decreases from 268.4 mm to 254.3 mm. The weight of the vehicle is also reduced from 716.85 kg to 710.4 kg. It can be seen that after the deterministic optimization, the collision evaluation indicators have been improved to varying degrees, the overall crashworthiness of the vehicle has been improved to some extent, and the vehicle mass has also been reduced.
5. Conclusion
To sum up, 100% frontal impact experiment was conducted in this paper. Eight plate thicknesses of components that have a greater impact on collision performance were selected as design variables, and the peak acceleration of the lower end of pillar B, the vehicle mass m and the intrusion of three key points were taken as responses. Seventy sets of training data on design variables and responses were obtained by means of DOE experimental design. According to the training data, the Kriging approximate model was established, and the prediction accuracy was evaluated. The results showed that the prediction accuracy of the approximate model basically met the requirements, which could be used in the following optimization design. And then PSO algorithm was used, the optimized result indicated that $a_{\text{max}}$ and $m$ decreased by 7.6% and 0.87%, and D1, D2 and D3 decreased by 7.7%, 3.1% and 5.3%, respectively, which still had a large room for improvement.

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