Optimization study on the compressive strength of a passenger vehicle roof

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Abstract. In order to improve the compressive strength of a passenger vehicle roof, in accordance with the Roof Crush Resistance of Passenger Cars (GB26134-2010), the paper rematches the main parts of the roof thickness parameters and optimizes the maximum compressive resistance using finite element analysis, experimental design, the establishment of approximate model and optimization. The results show that, by optimization and rematch, the maximum compressive resistance of roof increased by 3564N and improved the roof safety performance in the case of constant vehicle weight.

1. Introduction

Statistics show that, in Australia, the rolling accidents have resulted in 27% of traffic fatalities each year [1]. In Europe, 20% of all traffic fatalities account for rolling accidents [2]. In the United States, although the number of rolling accidents accounts for only 2.4% of all traffic accidents, 33% of the deaths in traffic accidents are due to rolling accidents [3]. In China, the proportion of rolling accidents increases with the decrease of the proportion of frontal crash and the side crash. At the same time, the rolling accident of our country also shows the characteristics of the serious accident and causes to group death and injury, and it has bad social influence [4]. Therefore, reducing the damage caused by rolling accident has great economic and social significance. So it is very important to research the vehicle roof safety performance.

For the overseas study, Mao et al. successfully achieved quasi-static crush simulation of the roof under different loading angles, and proposed the load angle of the car under extreme conditions. The roll angle and pitch angle of the rigid wall should be 45° and 10°, respectively [5]. Tahan et al. utilized two different loading angles to simulate the static collapse of a SUV roof, and validated its simulation results through experiments. The optimal design and research was carried out for the important bearing structures and a certain optimization effect was achieved [6]. Chen et al. proposed a simulation test method for the vehicle rollover. The simulation results are in good agreement with the test results. An effective tool was provided for the simulation and evaluation of vehicle structural safety design [7]. A lot of researches on roof strength have also been done in China. Liu et al. researched the car roof’s model characteristics, dent resistance and other structure performance by the finite element numerical simulation. The static and dynamic performance of the car roof structure is
systematically evaluated and the corresponding evaluation criteria and applicable scope are given. The evaluation system under each condition is integrated and a reasonable comprehensive evaluation system is obtained. It provides a reference for the vehicle design or related roof products [8]. Tang and Zhao analyzed the compressive strength of vehicle roof in accordance with the Roof Crush Resistance of Passenger Cars. She found design points of the compressive strength of roof through CAE analysis method [9].

Rolling accidents are the important factors that cause casualties and property losses. Therefore, it has great significance to study how to improve the compressive strength of roof. In this paper, a method to improve the compressive strength of roof is proposed based on the original car by means of finite element analysis and optimal matching of key components of the roof.

2. Modeling of the static compression of vehicle roof

2.1. FEM of the Static compression of vehicle roof

The finite element model used in this paper is a finite element model of a car provided by NCAC (National Crash Analysis Center). The weight of the car is 1534kg. In accordance with regulations, the vehicle is rigidly fixed on a rigid level during the test. The rigid plate used in the test was 1869 mm long and 762 mm wide, and it is required that the longitudinal axis of the rigid plate is parallel to the vertical plane passing through the longitudinal centerline of the vehicle. And in the side view, the longitudinal inclination angle of the longitudinal axis of the rigid plate is 5° downwards. In the front view, the camber angle of horizontal axis is 25° horizontally downward. The front end of the longitudinal axis of the rigid plate is 254mm forward than the initial point of car roof loading, which has a tolerance of 10mm. In the actual vehicle test, the rigid plate is loaded at a constant loading speed of not more than 13mm/s and is completed in 0.12s. The loading displacement does not exceed 127mm when the specified load is reached. The final finite element model is shown in Figure 1.

2.2. The analysis of simulation reliability

Figure 2 is the energy curve of the finite element model, the most important of which is the total energy, internal energy, kinetic energy, hourglass energy and interface energy. Each energy curve smooth transition, and hourglass energy, interface can account for a very small proportion. The change of total energy, internal energy and kinetic energy conforms to the actual theoretical analysis, so the finite element model and the result analysis are credible.

3. The evaluation method of the compressive strength

The evaluation method of the static collapse test of vehicle roof in the American Road Safety Insurance Association (IIHS) is based on the ratio of the maximum compressive resistance to the
vehicle weight (SWR) during the static collapse process of vehicle roof to determine the ability of the roof to resist static pressure.

$$SWR = \frac{F}{G}$$  \hspace{1cm} (1)

Where: $G$ is the total gravity of the car and $F$ is the maximum compressive resistance of roof.

The American Highway Safety Assurance Association's current star rating criteria for roof strength are: SWR to 2.5 ~ 3.25 is passing, 3.25 ~ 4 is good, 4 or more is excellent, and less than 2.5 is poor. After a comprehensive consideration, the paper requires that SWR is at least 3.

Figure 3 is the compressive resistance of roof and rigid plate displacement curve obtained by the original vehicle finite element model simulation. From the figure, we can see that the compressive resistance reached a maximum of 47014N when the rigid surface moved 90mm downwards in normal direction. The car's curb weight is 1534kg, so the SWR is 3.06.

4. Optimization design

In the compressive strength of the vehicle roof, the A-pillar, the B-pillar, the roof rail and the roof beam are the major bearing and transmission parts. Their displacement would directly decide the survival possibility of the passenger. Therefore, the maximum compressive strength of the vehicle roof can be optimized by changing the structural parameters of the A-pillar, the B-pillar, the roof rail and the roof beam. In this area, the A-pillar reinforcement plate, the A-pillar inner plate, the roof rail reinforcement plate, the roof rail, the B-pillar outer plate and the roof front beam are mainly selected as optimization objects. The most important factor affecting compressive strength is the thickness of the part after the part material is determined. By optimization, the thickness parameters of each part can be re-matched to achieve the maximum compressive resistance. Taking into account the installation space and positioning relationship of the original parts in the body, the thickness parameters are redesigned on the basis of not changing the original vehicle shape. The initial value and range of the parameters are shown in Table 1.

Table 1. The initial value and range of design parameter.

| Part Name          | A-pillar reinforcement plate | A-pillar inner plate | Roof reinforcement plate | Roof rail | B-pillar outer plate | Roof front beam |
|--------------------|----------------------------|----------------------|--------------------------|-----------|----------------------|-----------------|
| Test variable      | $T_1$                      | $T_2$                | $T_3$                    | $T_4$     | $T_5$                | $T_6$           |
| Initial thickness  | 1.5                        | 1.7                  | 2                        | 1.5       | 1.8                  | 1.85            |
| Design range       | 1 ~ 1.5                    | 1 ~ 2.4              | 1.5 ~ 2.5                | 1 ~ 2     | 1.2 ~ 2.4            | 1.2 ~ 2.5       |
The experimental design is the key link in the process of establishing approximate model. Obviously, the independent variables in this design are continuous in the fixed range. The traditional experimental design method is difficult to meet the requirements of the sample point selection, so this section utilizes the optimal Latin hypercube test method. This method makes all test points distributed as far as possible in the design space, with very good spatial filling and equalization. Number of test is set to 16 times; test evaluation index is the maximum compressive resistance of the roof $F$ and total mass of parts $M$. Specific experimental design scheme and results are shown in Table 2.

| Test number | $T_1$ (mm) | $T_2$ (mm) | $T_3$ (mm) | $T_4$ (mm) | $T_5$ (mm) | $T_6$ (mm) | $M$ (Kg) | $F$ (N) |
|-------------|------------|------------|------------|------------|------------|------------|---------|--------|
| 1           | 1.6        | 2.4        | 2.1        | 1.2        | 2.16       | 1.633      | 15.04   | 50921  |
| 2           | 1.733      | 1          | 2.167      | 1.067      | 1.36       | 1.72       | 11.18   | 44709  |
| 3           | 1.667      | 1.747      | 2.5        | 1.667      | 1.6        | 1.287      | 13.29   | 46795  |
| 4           | 1.533      | 1.467      | 2.033      | 2          | 2.4        | 1.46       | 14.79   | 47388  |
| 5           | 1.267      | 2.213      | 2.3        | 1.733      | 1.84       | 2.5        | 15.33   | 47640  |
| 6           | 1.867      | 1.56       | 1.5        | 1.333      | 1.92       | 1.373      | 12.65   | 49177  |
| 7           | 1.8        | 1.933      | 1.567      | 1.867      | 2.08       | 2.327      | 15.08   | 48879  |
| 8           | 1.2        | 1.28       | 2.433      | 1.267      | 2.24       | 1.893      | 14.06   | 47743  |
| 9           | 1.067      | 1.187      | 1.833      | 1.4        | 1.68       | 1.2        | 11.2    | 46082  |
| 10          | 1          | 1.84       | 1.633      | 1.533      | 2.32       | 1.98       | 14.38   | 49171  |
| 11          | 2          | 1.373      | 2.367      | 1.6        | 2          | 2.24       | 14.76   | 47098.5|
| 12          | 1.933      | 2.12       | 1.967      | 1.467      | 1.2        | 2.067      | 13.02   | 44737  |
| 13          | 1.333      | 2.307      | 1.767      | 1.933      | 1.52       | 1.547      | 13.36   | 46763  |
| 14          | 1.467      | 1.653      | 1.7        | 1          | 1.76       | 2.413      | 13.05   | 48018  |
| 15          | 1.4        | 1.093      | 1.9        | 1.8        | 1.44       | 2.153      | 12.12   | 44125.6|
| 16          | 1.133      | 2.027      | 2.233      | 1.133      | 1.28       | 1.807      | 12.22   | 45533.6|

When the finite element model is optimized, it is necessary for the model to repeat operations multiple times to filter out the optimal value, which takes a lot of time. In view of this feature, the project proposes to use the approximate model to offset the shortcomings of huge time cost. Approximation Models are methods of utilizing mathematical tools to establish a model that highly approximates the input parameters and response parameters. Approximation Models make resolution efficiency of optimization problem in engineering improve greatly and play a good effect. In this paper, the Kriging approximation model is adopted. The approximation model is simple, easily operated, and widely used in engineering.

This paper establishes the Kriging model with different parts thickness $T_1$-$T_6$ as independent variables, the maximum compressive resistance of the roof $F$ and total mass of parts $M$ as responses. The model established by the Kriging method is expressed in the form of 3D Graphs. Because the Z-axis represents the response value of the approximate model in the 3D Graphs, each of the 3D Graphs can only contain two variables. The approximate model of response $F$ for $T_1$ and $T_2$ is shown in Figure 4. The approximate model of response $F$ for $T_3$ and $T_4$ is shown in Figure 5.
We can rely on the model to optimize the maximum compressive resistance after establishing a high-precision approximation model.

The ultimate goal of optimization the design is to make the maximum compressive resistance as large as possible and reduce cab deformation when the car is rolling on the basis of not increasing or reducing the quality of the vehicle, so as to ensure safe living space of passenger. In this paper, multi-island genetic algorithm (MIGA) is used to optimize the thickness of different parts on the basis of approximate model. The algorithm is a parallel distribution algorithm (PDGAs) optimized by Kaneko et al.[10], Department of Knowledge Engineering, Doshisha University, Japan. It has better global convergence and computational efficiency than traditional genetic algorithms.

The mathematical model of the optimization problem is shown in equation (2).

\[
\begin{align*}
\text{optimization objective:} & \quad \min \{F\} \\
\text{constraint condition:} & \quad M \leq 13.38 \\
\text{variable range:} & \quad 1.0\text{mm} \leq T_i \leq 2.0\text{mm} \\
& \quad 1.0\text{mm} \leq T_2 \leq 2.4\text{mm} \\
& \quad 1.5\text{mm} \leq T_3 \leq 2.5\text{mm} \\
& \quad 1.2\text{mm} \leq T_4 \leq 2.4\text{mm} \\
& \quad 1.2\text{mm} \leq T_5 \leq 2.5\text{mm}
\end{align*}
\]  

The total number of iterations of the multi-island genetic algorithm is 1000, and the optimization results are shown in Table 3.

| Optimization results | T1 (mm) | T2 (mm) | T3 (mm) | T4 (mm) | T5 (mm) | T6 (mm) | M (Kg) | F (N) |
|----------------------|---------|---------|---------|---------|---------|---------|--------|-------|
|                      | 1.46    | 2.27    | 1.5     | 1       | 2.08    | 1.2     | 13.378 | 51516 |
The values of the optimized $T_1$-$T_6$ are brought into the finite element model for verification. After verification, the maximum compressive resistance of roof is 50578N and the error is 1.8%, which indicates that the result is credible after optimization.

5. Conclusions
This paper takes the roof safety as the research object. On the basis of not increasing the quality of the vehicle, it is expected to match and optimize the thickness of the key components of the roof to enhance the safety of the roof.

First, select the key components that affect the safety of the roof; then, use the optimal Latin hypercube method to design 16 sets of experiments. According to the experimental results, a Kriging approximation model is established; the multi-island genetic algorithm is used to optimize the components on the base of approximate model. Under the premise of not increasing the quality of the body, the maximum compressive resistance increased by 7.6% and the roof safety is improved. It provides a feasible path for the improvement of vehicle safety.

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References
[1] Grzebieta R H, et al. 2010 How Stronger Roofs Prevent Diving Injuries in Rollover Crashes, in International Crashworthiness Conference. Paper No. 2010-021. Washington D.C. ICrash 2010-021
[2] Frimberger M, et al. 2000 Influences of Parameters at Vehicle Rollover, in SAE paper. 2000-01-2699: Society of Automobile Engineers
[3] Strashny A 2007 An Analysis of Motor Vehicle Rollover Crashes and Injury Outcomes.2007a, National Highway Traffic Safety Administration
[4] Xie B Y, Zhu X C, Diao Z X 2008 Study on Vehicle Tilting Test Method. Infats Proceedings the Sixth International Forum of Automotive Traffic Safety
[5] Mao M, Chirwa E C, Chen T, et al. 2005 Numerical Analysis of a Small European Vehicle under Rollover Condition. Proc. IMechE Vol. 219 Part D. Automobile Engineering 1396-1379
[6] Tahan F, Digges K, Mohan P 2010 Sensitivity Study of Vehicle Rollovers to Various Initial Conditions Finite Element Model Based Analysis. The National Crash Analysis Center
[7] Chen T, Chirwa E C, Mao M, et al. 2007 Rollover Far Side Roof Strength Test and Simulation. Int. J. Crashworthiness 12(1):29-40
[8] Liu S, Gao Y K, Zhang K P 2012 Comprehensive Performance Analysis and Evaluation of Car Roof Structure. Automotive Technology 01: 17-22
[9] Tang B and Zhao X H 2011 Development of a model for "compressive strength at the top of passenger cars". Automotive and Accessories 40: 32-35
[10] Lai Y Y, Jiang X, Fang L Q, et al. 2012 Isight Parameter Optimization Theory and Example Explanation. Beijing: Beihang University Press 139-142