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MECHANICAL AND AERONAUTICAL ENGINEERING, THERMODYNAMICS

Optimized design of truck cab lightweighting based on sensitivity hierarchical comparative analysis method

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Abstract. The relative sensitivity analysis method is important in the field of vehicle lightweighting. Combined with optimization algorithms, experiment of design (DOE), etc., it can efficiently explore the impact of unit mass of components on performance and search for components with lightweight space. However, this method does not take into account the size level of each component and the order of magnitude differences in sensitivity under different operating conditions. Therefore, this paper proposed a sensitivity hierarchical comparative analysis method, on the basis of which the thicknesses of 10 groups of components were screened out as design variables by considering the lightweighting effect, cab performance, and passive safety. Through the optimal Latin hypercube method, 70 groups of sample points were extracted to carry out the experimental design, the Kriging surrogate model was established and the NSGA-II genetic algorithm was used to obtain the Pareto optimal solution set, and ultimately a weight reduction of 13.13 kg was realized under the premise that the entire performance of the cab improved.

Keywords: truck cab; lightweight; sensitivity analysis; surrogate model; sensitivity hierarchical comparative analysis.

1. INTRODUCTION

In recent years, a series of policies have been introduced to expand domestic demand and stabilize the economy in China, and commercial vehicles, as a key pillar to boost China's economy and infrastructure construction, will usher in greater development opportunities. As global warming and the energy crisis gradually evolve, lightweighting, which can effectively reduce vehicle fuel consumption and emissions, has become an important trend and a key issue in the automotive industry.

In the field of automobile lightweight design, the relative sensitivity analysis method, based on the global sensitivity analysis method, takes the quotient of performance sensitivity and mass sensitivity as a criterion, which can find out the design variables of those components in the body-in-white structure that are relatively insensitive to performance but sensitive to mass. Combined with topology optimization [1, 2], design of experiment (DOE) [3], establishment of surrogate models [4], and other optimization methods, the design goals can be well achieved, and there are broad application prospects. Sobol's sensitivity analysis method, a variance-based Monte Carlo method, is a typical representative of global sensitivity analysis, which comprehensively considers the distribution and shape of probability density functions of each factor, and lays the foundation for subsequent sensitivity analysis in the field of body design optimization [5–7]. Sobieszczanski-Sobieski *et al.* [8] developed a surrogate model based on NVH sensitivity analysis and crash conditions to achieve optimization of a highly nonlinear iterative process. Kim *et al.* accomplished the optimization of the vehicle half shafts through sensitivity analysis, and the acceleration was reduced by about 50% at a specific frequency [9]. Ferro *et al.* used software for optimization purposes through 51 lines of code, relying on sensitivity analysis [10]. Jin *et al.* used payload parameter sensitivity analysis to effectively predict the the relationship between the vehicle payload parameters and system state estimation of electric vehicles in the lightweighting process [11]. Wang used a combination of relative sensitivity and contribution analysis to select components and achieved multi-objective optimization of commercial vehicle cab by establishing a Kriging surrogate model [12]. Jana *et al*. [13] show how a global sensitivity matrix on metamodels is used to analyze the interactions and to interdisciplinary optimize the design targets. Ou took an approach combining sensitivity analysis and topology optimization to achieve the targeted performance while reducing the weight of the body-in-white by 13.3% [14].

Wang Dengfeng *et al*. conducted a sensitivity analysis on the main structural parameters of mortar base plates based on DOE, combined with multiple optimization methods, and ultimately achieved a 33.2% lightweight reduction of the plate [15]. However, the traditional relative sensitivity analysis method, as a quantitative calculation method, does not fully consider the component size level and has some limitations in determining the priority of optimized components.

To better determine the optimization priority of components and design the component selection scheme more scientifically and reasonably, this paper proposes a sensitivity hierarchical comparative analysis method, and on this basis, the lightweight optimization design of truck cabs is carried out through experimental design and surrogate model.

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2. CAB RAW ANALYSIS

2.1. Finite element model

The cab model used in this paper is provided by the enterprise. Unnecessary hooks, holes, and chamfers are removed in UG, which has less influence on the simulation results, and the cab geometry model is imported into Hypermesh for meshing. The cab skeleton is mostly a beam and panel structure, so the shell cell grid is used, and the components are connected by welding and bolting. As a numerical analysis method, finite element analysis needs to consider the convergence of different mesh sizes in practical applications. The convergence analysis is carried out with 10 mm, 8 mm, 5 mm, and 4 mm mesh models respectively, and the bending condition is used as the verification condition. By analyzing the several grid cell sizes and the equivalent stress at a certain place (Fig. 1), it can be seen that during the process of refining the grid size from 5 mm to 4 mm, the magnitude of the curve change is not large, and the stress error is less than 1%. It can be assumed that the 5 mm mesh can ensure the convergence of the mesh and meet the accuracy requirements of the calculation, so the mesh size of the cab model in this paper is 5 mm. The finite element model of the truck cab is shown in Fig. 2.

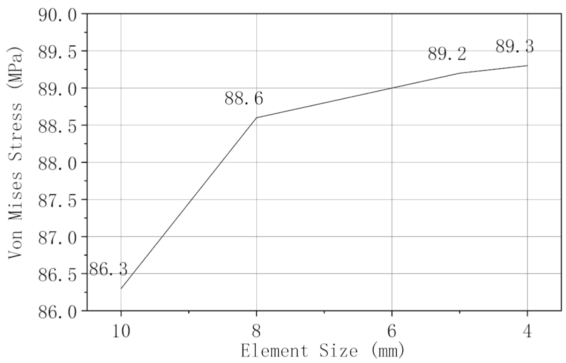


Fig. 1. Convergence analysis

Fig. 2. Finite element model

2.2. Cab static analysis

Simulation and analysis calculations including cab body stiffness, strength of four typical working conditions, and free modes [16] were carried out by Hypermesh software to obtain the original cab performance indexes. Take the bending condition as an example, constrain the front suspension of the cab in the Z-direction translational degree of freedom, constrain the rear suspension in the Y- and Z-direction translational degrees of freedom, and apply a total of 6800 N of vertical downward load at the two front seats, the constructed model is shown in Fig. 3, and the results of each performance index are shown in Table 1, which are all in line with the relevant requirements.

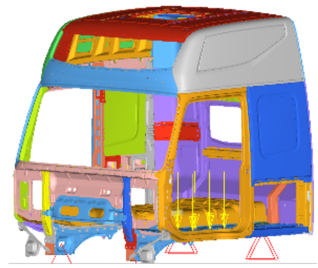


Fig. 3. Bending working condition model

In Table 1, the bending stiffness is the ratio of two times the load applied to the front seats to the average Z-direction maximum displacement of the left and right longitudinal beams in this condition, and the torsional stiffness is the ratio of the applied torque to the relative degrees of rotation of the left and right front suspensions in this condition [17].

2.3. Cab crashworthiness data

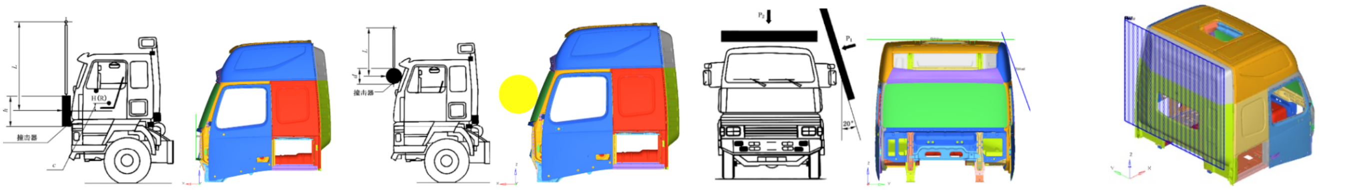
According to GB 26512-2021 "The protection of the occupants of the cab of commercial vehicles" standard [18], the finite element model of each passive safety condition established is shown in Fig. 4, including 1. Frontal impact test; 2. A-pillar impact test; 3. Top strength test; 4. Rear enclosure strength test. Take the frontal impact condition as an example: the impactor is a steel rigid body with a total weight of 1500 kg, a length of 2500 mm, and a width of 800 mm, and the cab is impacted from front to back with an initial velocity of 8.57 m/s.

Simulation results can replace actual vehicle testing [19] and the deformation at each moment of the four-case simulation is shown in Fig. 5.

The truck cab has less deformation in the A-pillar impact test, top strength test, and rear enclosure strength test, and the survival space of the occupants is enough to ensure, so the subsequent

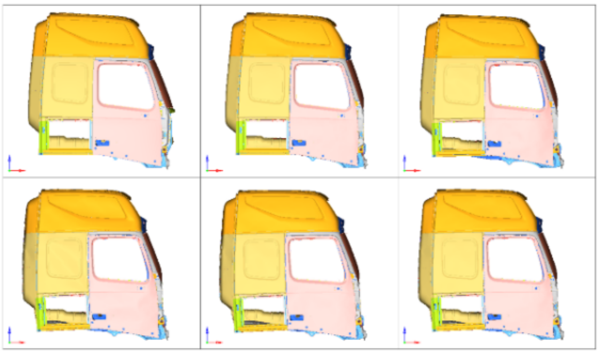
Table 1
Mass, modal, stiffness, and strength of cabs

Performance	Mass [kg]	First-order modal [Hz]	Bending stiffness [N·mm^{-1}]	Torsion stiffness [N·mm·deg^{-1}]	Maximum stress [MPa]			
					Vertical load condition	Acceleration conditions	Braking condition	Steering condition
Value	385.26	15.33	7645.16	17548.65	102.1	111.4	103.0	131

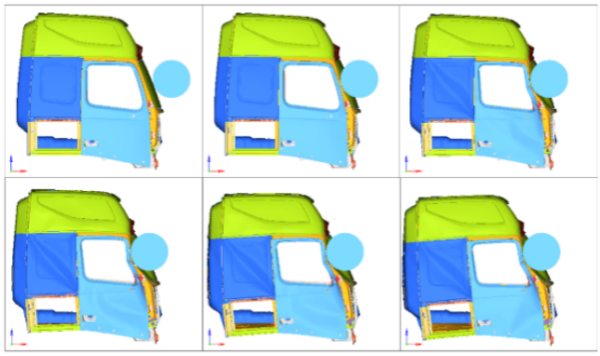


(a) Frontal impact test **(b)** A-pillar impact test **(c)** Top strength test **(d)** Rear enclosure strength test

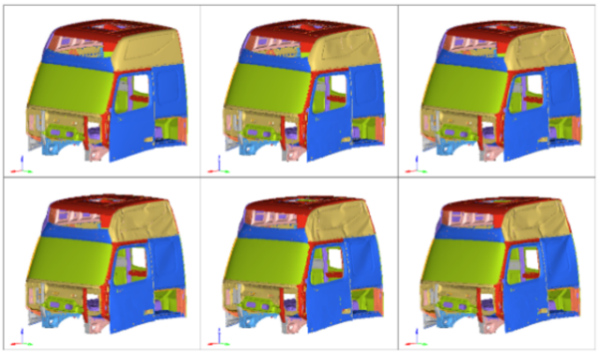
Fig. 4. Four crash condition models



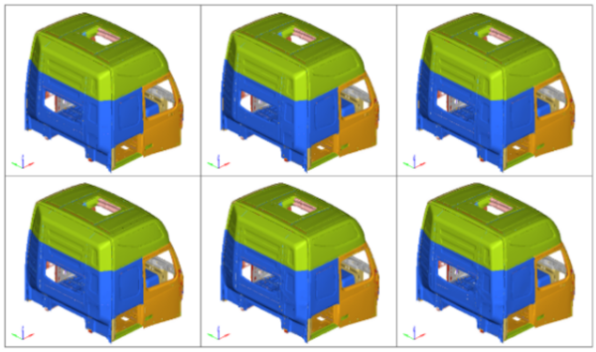
(a) Deformation in frontal impact test



(b) Deformation in A-pillar impact test



(c) Deformation in top strength test



(d) Deformation in rear enclosure strength test

Fig. 5. Deformation at each moment of passive safety four-case simulation test (0/20/40/60/80/100 ms)

optimization of this paper will focus on considering the safety of the occupants in the frontal collision, and the X-direction intrusion of the front enclosure panel, and X-direction velocity and acceleration curves of the bottom of the B-pillar in frontal impact test are shown in Figs. 6–9.

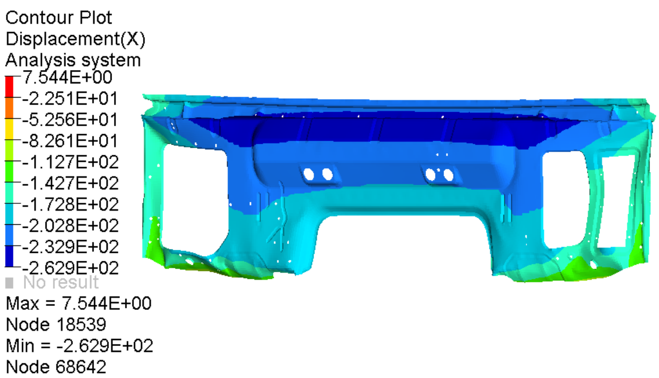


Fig. 6. Cloud view of X-direction intrusion in the front perimeter panel

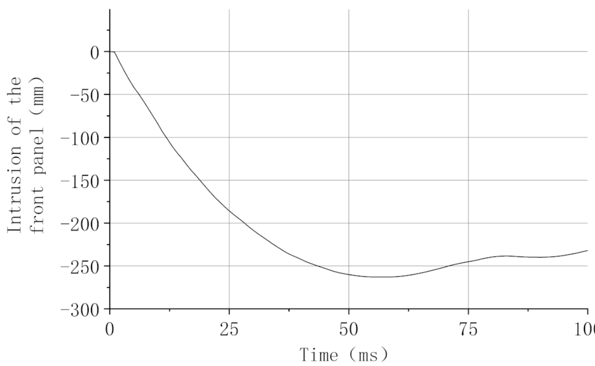


Fig. 7. X-direction intrusion curve of front perimeter panel

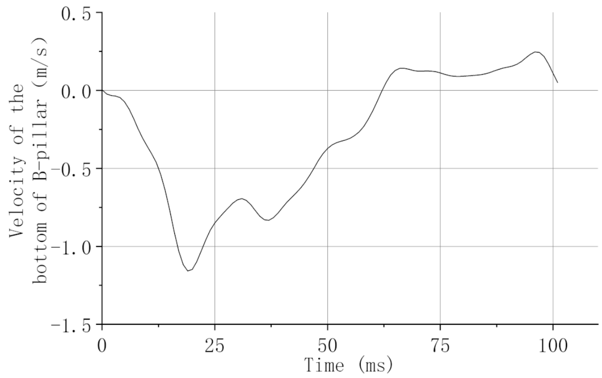


Fig. 8. X-directional velocity at the bottom of B-pillar

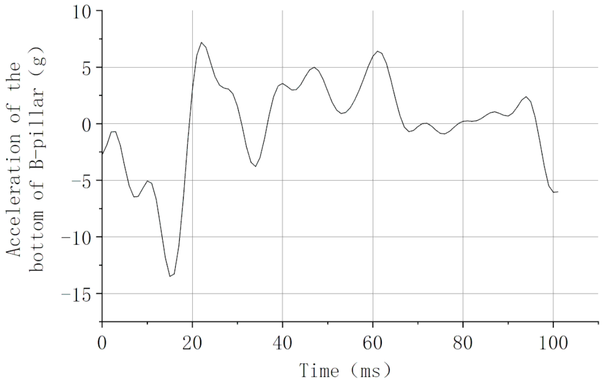


Fig. 9. X-directional acceleration at the bottom of B-pillar

3. COMPONENTS SELECTION

3.1. Sensitivity analysis

In elastostatics, its finite element equilibrium equation can be expressed as [20]:

$$\mathbf{K}(x)\cdot\mathbf{U}(x)=\mathbf{F}, \tag{1}$$

where $\mathbf{K}(x)$ is the stiffness matrix of the structure, $\mathbf{U}(x)$ is the displacement vector, $\mathbf{F}$ is the external load, and x is the structural variable (such as shape, thickness, etc.).

By taking the partial derivative of x at both ends of equation (1) and shifting the term, equation (2) can be obtained:

$$\frac{\partial\mathbf{U}(x)}{\partial x}=-\mathbf{K}^{-1}(x)\frac{\partial\mathbf{K}(x)}{\partial x\mathbf{U}(x)}. \tag{2}$$

Therefore, in the static analysis of the cab, the sensitivity r of the thickness of each component of the cab to various performances can be expressed as:

$$\mathrm{r}=\frac{\partial f(x)}{\partial x}, \tag{3}$$

where $f(x)$ is the performance objective function, and x is the component plate thickness.

Taking the thickness variation of each component of the truck cab used in this paper as the independent variable, and taking the mass, the corresponding displacement of the selected points for calculating the stiffness of each working condition, and the first-order modes as the strain variables, the sensitivity analysis of each component of the cab is carried out, and the results of its mass sensitivity r_m, bending stiffness sensitivity r_b, torsional stiffness sensitivity r_t and first-order mode sensitivity r_{fm} are shown in Fig. 10.

The relative sensitivity of comprehensive performance are calculated in equations (4) and (5) [21], where R_b is the relative sensitivity of bending stiffness, R_t is the relative sensitivity of torsional stiffness, R_{fm} is the relative sensitivity of the first-order modes, R is the relative sensitivity of the comprehensive performance, and the final results are shown in Table 2 (without smaller mass components such as nut plates):

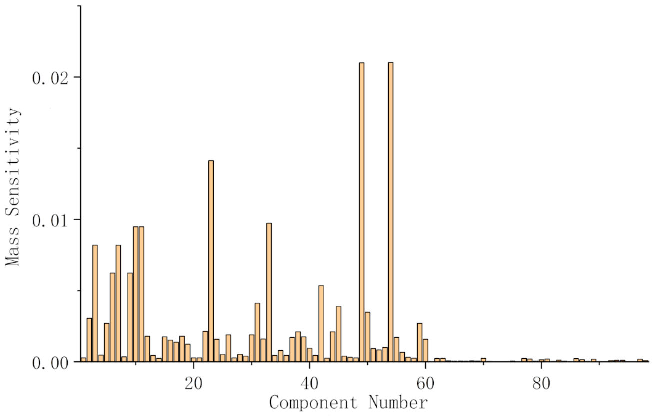
$$R=0.4R_b+0.4R_t+0.2R_{fm}, \tag{4}$$

$$R_b=r_b/r_m,\quad R_t=r_t/r_m,\quad R_{fm}=r_{fm}/r_m. \tag{5}$$

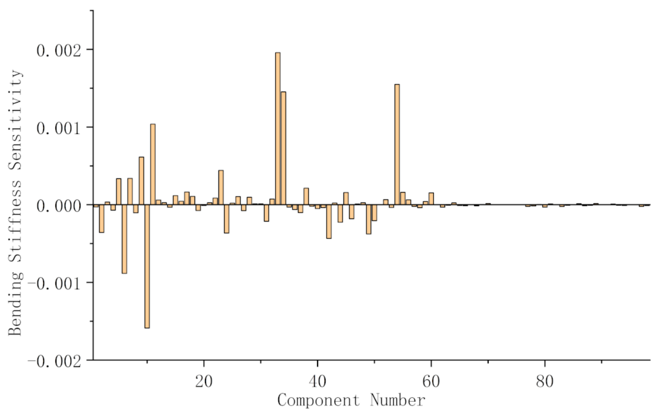
As shown in the table below, traditional sensitivity analyses often use a method of assigning weighting factors to the sensitivity of each operating condition to be considered in aggregate. However, the change of component thickness will inevitably have different levels of influence on the performance under different working conditions, such as the change of the thickness of the

Table 2
Optimization strategy based on traditional sensitivity analysis

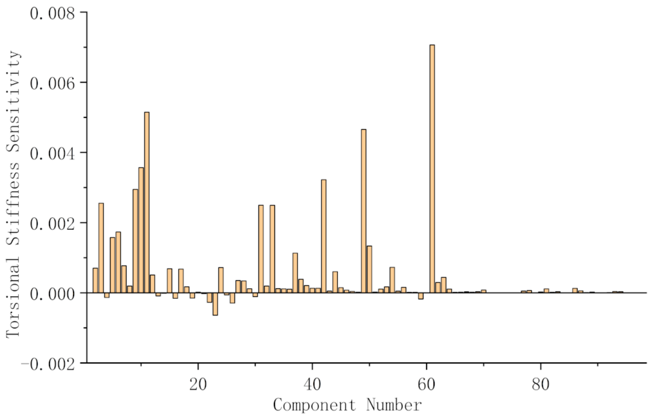
Component number	Name of the component	Relative sensitivity of comprehensive performance	Optimization methods
5	Left rear enclosure side beam	9.59015	Prioritize thickening
2	Inner panel of the upper frame of the side enclosure	8.42594	
59	Right rear enclosure side beam	6.86485	
8	Door frame front upper corner reinforcement panel	5.91771	
...	...	...	
42	Windshield upper skeleton inner panel	–2.33375	
44	Door rear frame inner panel	–2.42411	
50	Cab windshield upper skeleton inner panel	–3.68667	
4	Liner bracket assembly	–7.74787	Prioritize thinning



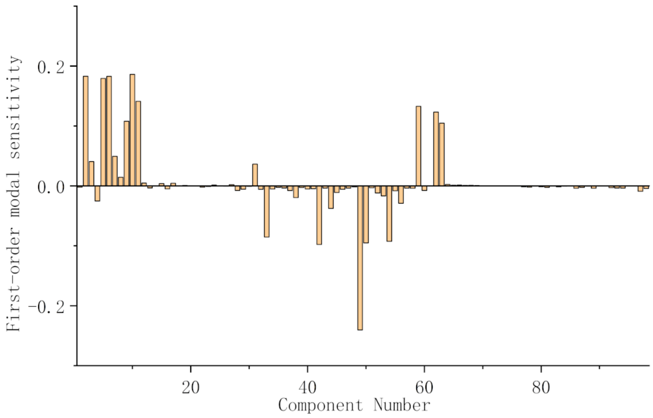
(a) Mass sensitivity of each component



(b) Bending stiffness sensitivity of each component



(c) Torsional stiffness sensitivity of each component



(d) First order modal sensitivity of each component

Fig. 10. Sensitivity analysis of the thickness of truck cab panels

upper outer panel of the cab rear enclosure will significantly affect the first-order modes, while the impact on the overall stiffness is small. Secondly, the results of the data of the sensitivity analysis are also affected by the selection of the response points and constraints of the finite element model. This often causes differences in the order of magnitude between the results of the sensitivity analysis data of each working condition, and the sensitivity of each working condition has extremely large or small value points individually, which leads to the scale imbalance and distortion of the weighted comprehensive performance sensitivity data.

In addition, most of the traditional sensitivity analyses are based on the ratio of performance sensitivity to mass sensitivity, i.e. relative sensitivity, to find the component that has the largest or smallest impact per unit of mass on the overall performance of the vehicle. However, this method pays too much attention to the quotient, focuses on the relative size, and ignores the influence of the size level of the component itself. For example, the mass and performance sensitivity of the cab floor are on the large side, and the mass and performance sensitivity of the nut plate are on the small side, their relative sensitivities are similar, so it is not possible to determine their optimization priority; another example is a small-sized toolbox cover, whose mass sensitivity is on the large side and performance sensitivity is on the small side, which is a more ideal lightweight component from the perspective of the relative sensitivity. But its small size makes the lightweighting of this component not ideal in the entire vehicle scale. Therefore, this method has problems such as the inability to determine the priority of component optimization and relatively less than ideal lightweighting.

3.2. Sensitivity hierarchical comparative analysis

To solve the above two types of problems, this paper improves the traditional quantitative type of sensitivity analysis and proposes a hierarchical comparative analysis of sensitivity analysis, the main realization steps are as follows (Fig. 11):

1. Normative sensitivity data

To avoid the overall high sensitivity data of some working conditions and dominate the sensitivity of other conditions, two data normalization algorithms of equations (6) and (7) are used to process the sensitivity data and defined as Method I and Method II, respectively, where r_i in both equations is the sensitivity of No. i component, r_i' is the updated sensitivity, $\max|r|$ is the maximum absolute value among sensitivity of all components, and $\max r$ and $\min r$ are the maximum and minimum

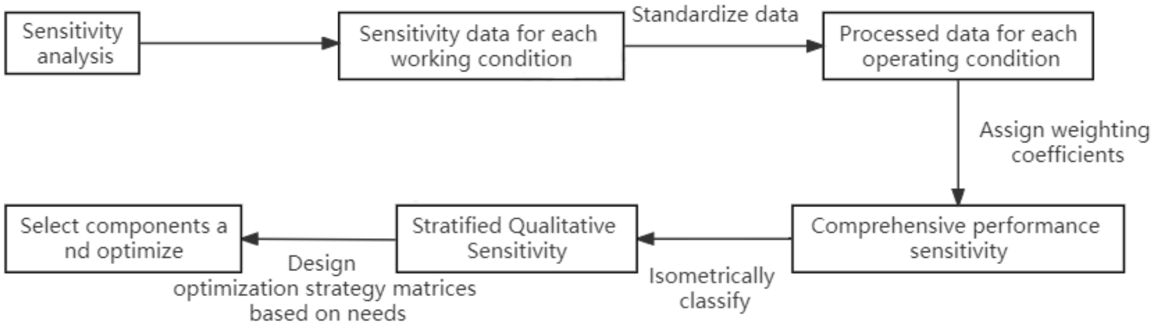


Fig. 11. Sensitivity hierarchical comparative analysis

values of sensitivity among all components:

$$r_i' = \frac{r_i}{\max|r|}, \tag{6}$$

$$r_i' = \frac{r_i}{\max r - \min r}. \tag{7}$$

The sensitivity data is processed by the two methods: 1) the sign of the data is unchanged, which ensures that the trend of the influence of panel thickness variations on the cab performance remains unchanged; 2) the range of the distribution is reduced, which offsets the dominant effect of the overall large sensitivity for some of the operating conditions.

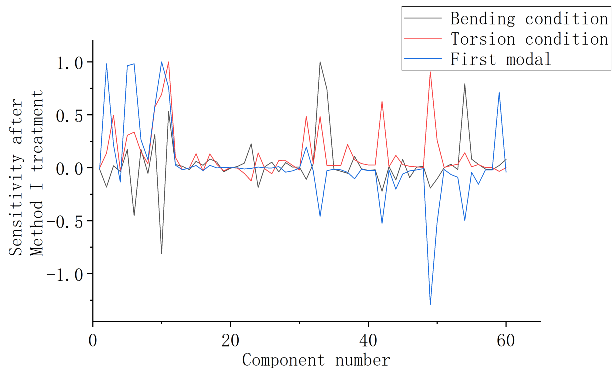
2. Weighted calculation of comprehensive performance sensitivity

The weighting coefficients are assigned to each working condition and the comprehensive performance sensitivity is calculated as shown in equation (8), where r_{cp} is the comprehensive performance sensitivity, r_b' is the normalized bending condition sensitivity, r_t' normalized is the torsional condition sensitivity, and r_{fm}' is normalized the first modal sensitivity. c_1, c_2 and c_3 are the weighting coefficients, referring to equation (4) and reference [21], 0.4, 0.4 and 0.2 are continued to be used in this paper. The results of the sensitivity data obtained after the processing of step 1 and step 2 are shown in Fig. 12, and the trend of the data after the processing of the two methods is roughly similar, with a certain degree of confidence.

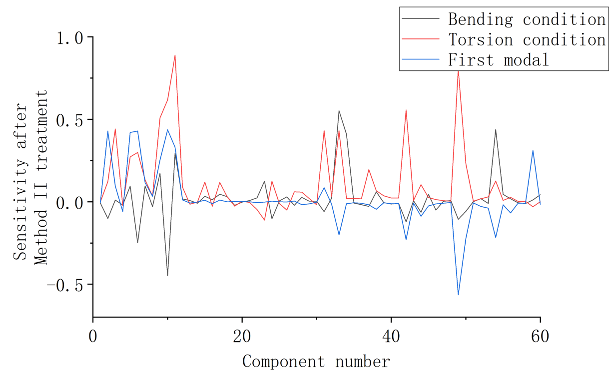
$$r_{cp} = c_1 r_b' + c_2 r_t' + c_3 r_{fm}'. \tag{8}$$

3. Hierarchical categorization of sensitivity

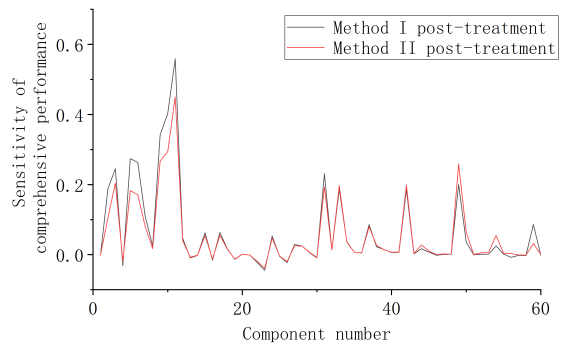
Based on the above, in order to give full consideration to the sensitivity ratio and size level of the components, the sensitivity data are divided into categories according to their numerical amplitude in a uniform and equidistant manner, defining the mass sensitivity of the components as three categories, namely, "Large, Medium and Small", and the comprehensive performance sensitivity of the components as four categories, namely, "Large, Medium, Small and Negative". Define the new evaluation index "hierarchical comparative analysis of sensitivity" for each component "mass sensitivity/performance sensitivity", a total of 12 levels, using the "ratio" form of qualitative analysis, rather than the traditional focus on "quotient" quantitative analysis, the cab components of the hierarchical sensitivity is



(a) Method I



(b) Method II



(c) Comprehensive performance sensitivity weighted for each working condition

Fig. 12. Sensitivity data after Method I and Method II processing

shown in Fig. 13. (In the cab model used in this article, there are no components at the Large/Small and Small/Medium levels, so these two levels are not indicated in the legend).

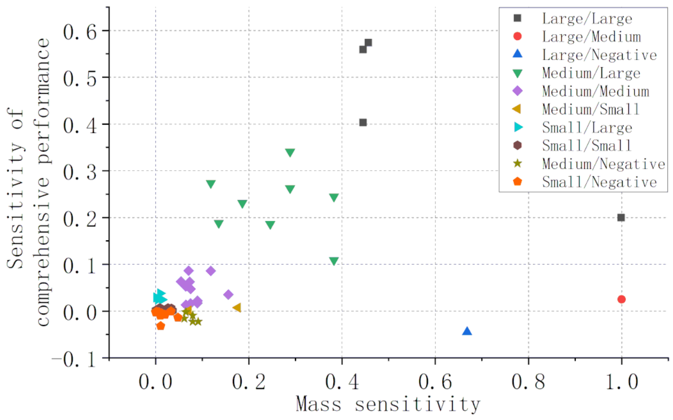


Fig. 13. 2-levels sensitivity distribution of each component

4. Sensitivity hierarchy-oriented optimization strategy design

After determining the 12-level category, the corresponding optimization strategy needs to be designed based on the sensitivity characteristics of each level. To fully meet the requirements of lightweighting and performance of the cab, the basic logic of the optimization scheme adopted in this article is that the performance is given priority in thinning and the weight is given priority in thickening. On this basis, the suggested optimization strategy of the sensitivity hierarchical comparative analysis method is shown in Table 3.

Taking "Large/Medium" as an example, it represents that when the thickness of the component is thickened, the mass increase is large and the increase in performance is moderate, and when the thickness is thinned, the mass decrease is large and the decrease in performance is moderate, so it can be appropriately thinned and the priority is lower than "Large/Small" and "Medium/Small" components. "Large/ Negative", for example, means that when the thickness of the component increases, the mass increases more and the performance decreases, while when the thickness is thinned, the mass decreases more and the performance increases, so it should be thinned and the priority is higher than "Medium/Negative" and "Small/Negative" components. "Large/Large", for example, means that the mass sensitivity and the comprehensive performance sensitivity are large, and changes in thickness will significantly increase or decrease the mass and comprehensive performance of the cab, making it difficult to efficiently balance lightweight and optimization effects, and therefore this type of component is not suitable for thickness optimization.

Table 3
Matrix of optimization strategies for sensitivity hierarchical comparative analysis

Type of "mass sensitivity/ performance sensitivity"	Suggested treatment of this type of component
Large/Large	Not suitable for thickness optimization
Large/Medium	Appropriate thinning with low priority
Large/Small	Appropriate thinning with high priority
Medium/Large	Appropriate thickening with low priority
Medium/Medium	Not suitable for thickness optimization
Medium/Small	Appropriate thinning with medium priority
Small/Large	Appropriate thickening with high priority
Small/Medium	Appropriate thickening with medium priority
Small/Small	No need to optimize
Large/Negative	Thinning with high priority
Medium/Negative	Thinning with medium priority
Small/Negative	Thinning with low priority

3.3. Selection of components to be optimized

To ensure optimization results, the selected design variables should not be too few. Car collision is a typical nonlinear problem, which takes an extremely long time to solve. Considering the difficulty of establishing subsequent surrogate models and solving with genetic algorithms, the selected design variables should not be too many. Therefore, taking into account the above situation and referring to engineering experience, combined with the actual situation of this cab model and sensitivity hierarchical comparative analysis data, 10 sets of components suitable for optimization were selected as design variables.

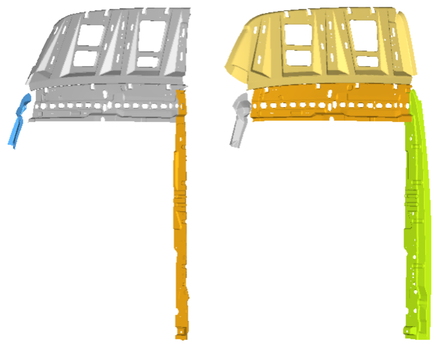
In the traditional sensitivity analysis method in Section 3.1, the components to be optimized are shown in Fig. 14, and the preferred thinning components are liner bracket assembly, cab windshield upper skeleton inner panel door rear frame inner panel, windshield upper skeleton inner panel. The components that are prioritized for thickening are large-sized components such as the inner panel of the upper frame of the side enclosure and rear enclosure side beam, and if these components are to be moderately thickened to improve performance, it is highly likely that the lightweighting effect will not be obvious.

The components to be optimized based on the sensitivity hierarchical comparative analysis method are ①–⑦, shown in Table 4, Fig. 15, and Fig. 16.

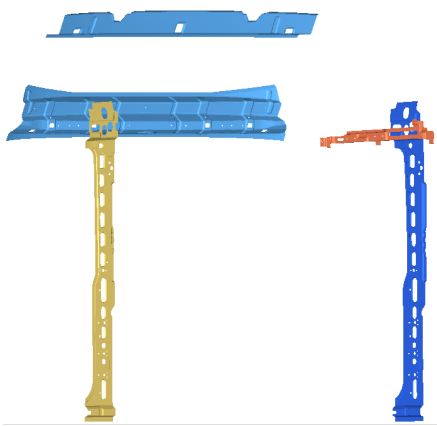
In addition, to fully consider the collision safety factors in the pre-lightweighting stage, this paper also selects some collision-sensitive components to participate in the optimization. In the frontal collision process of commercial vehicles, the longitudinal beam and floor structure are the main structures involved in deformation and energy absorption [22], and the change in the floor thickness will seriously affect the maximum intrusion [23]. In this paper, the main deformed components in the frontal collision simulation of truck cab are longitudinal beam, floor, front inner and outer panels, and left and right door frames, and their deformation is shown in Fig. 17. Considering the literature [22, 23], combined with the results of sensitivity analysis, the components shown in Table 5 are selected as frontal crash safety sensitive components and the thickness variations rang-

Table 4
Components to be optimized based on the sensitivity hierarchical comparative analysis method

Component	Component serial number	Component name	Treatment
①	23	Upper outer panel of the rear enclosure	Thinning with high priority, thickness variations ranging from 60% to 100%
②	16	Rear enclosure longitudinal beam	Thinning with medium priority, thickness variations ranging from 75%–100%
③	22	Rear enclosure cross-member	
④	26	Top cover and side panels	
⑤	34	Upper support panel	Appropriate thickening with medium priority, thickness variations ranging from 100%–125%
⑥	28	Lower front door corner reinforcement panel	
⑦	8	Door frame front upper corner reinforcement panel	



(a) Components prioritized for thickening



(b) Components prioritized for thinning

Fig. 14. Components to be optimized screened by the traditional sensitivity analysis

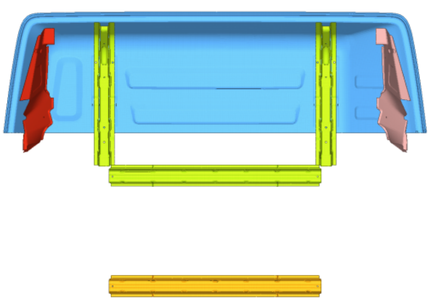


Fig. 15. Thinning component ① to ④

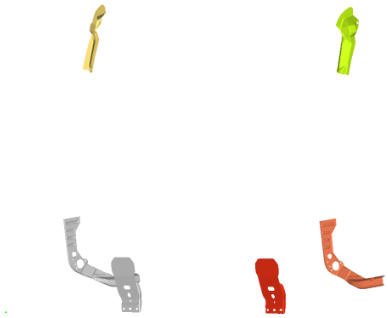
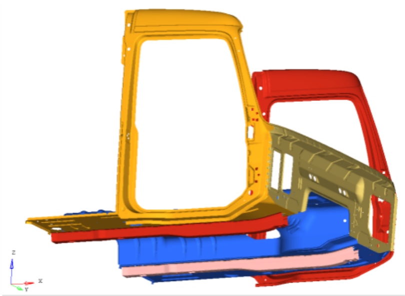
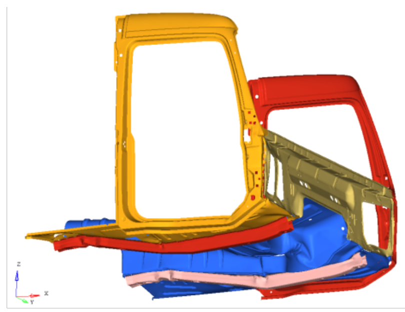


Fig. 16. Thickening component ⑤ to ⑥

ing from 85%–125% (Fig. 18). The thicknesses of components ① through ⑩ are the 10 factors for the subsequent construction of the approximate surrogate model.



(a) 0 ms



(b) 60 ms

Fig. 17. Deformation of the frontal impact safety components of the cab at 0 and 60 ms

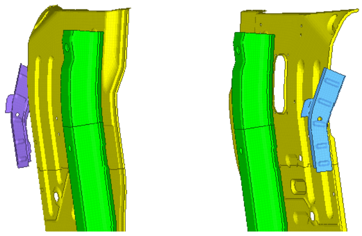


Fig. 18. Frontal crash safety sensitive components ⑧–⑩

Table 5

Frontal crash safety sensitive components

Component	Component serial number	Component name
⑧	22	Front section of left and right longitudinal beams
⑨	87	Left and right side front lower reinforcement panels
⑩	33	Front section of left and right floor

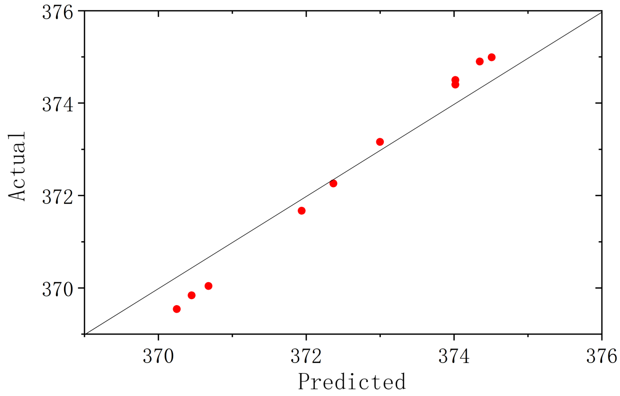
4. OPTIMIZATION MODELS

It is a typical multi-objective optimization problem to ensure the stiffness, modal, and other properties of truck cabs, and to introduce frontal crash safety factors in the pre-lightweighting stage for lightweight design. In this paper, the thickness of the screened 10 groups of panels is taken as the design variable x. With the objectives of minimizing the mass of the cab $f_{\text{mass}}(x)$ and minimizing the X-direction intrusion of the front enclosure panel $f_l(x)$ in the forward crash condition, and with the constraints of the peak acceleration at the bottom of the B-pillar $h_a(x)$ (g is the acceleration of gravity), the bending stiffness $h_b(x)$, the torsional stiffness $h_t(x)$, and the first-order modal $h_{fm}(x)$ greater than the original value, the final optimization model is established as follows:

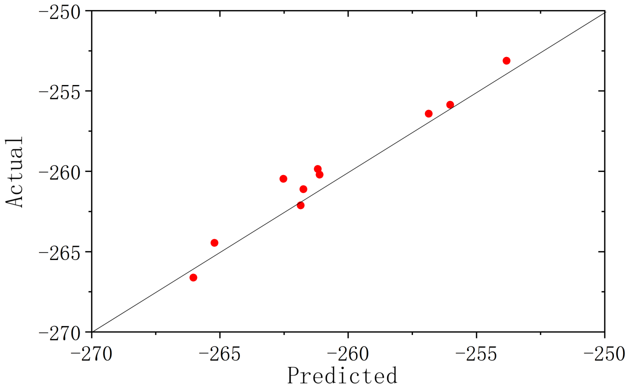
$$\begin{gathered} \text{find } x = (x_1, x_2, x_3, \ldots, x_{10}), \\ \min f(x) = \left[f_{\text{mass}}(x),\ f_l(x)\right], \\ s.t.\ \ h_a(x) \geq -13.44\ \text{g}, \\ h_b(x) \geq 7645.16\ \text{N} \cdot \text{mm}^{-1}, \\ h_t(x) \geq 17548.65\ \text{N} \cdot \text{mm} \cdot \text{deg}^{-1}, \\ h_{fm}(x) \geq 15.33\ \text{Hz}. \end{gathered} \tag{9}$$

In this paper, the optimal Latin hypercube method is adopted to sample 70 groups of sample points to ensure better parameter space coverage, reduce the nonlinear correlation between parameters, and provide more reliable statist ability in complicated nonlinear systems [24], and the sampling results and simulation results of the experimental design are shown in Table 6.

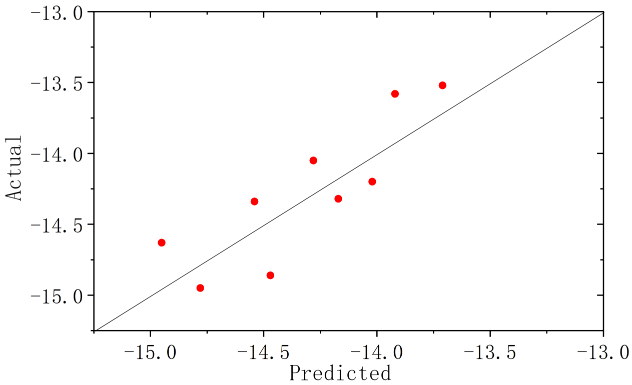
A Kriging approximate surrogate model with a good fit to the nonlinear conditions was established based on 70 sets of crash simulation tests [25], and 10 sets of data in the sample were selected as test points for R_2 detection, as shown in Fig. 19. The R_2 coefficient of the total mass of the cab is 0.94, the R_2 coefficient of the X-direction intrusion of the front enclosure outer



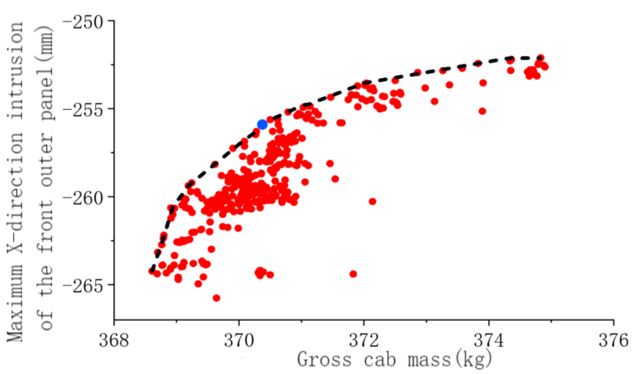
(a) Gross cab mass



(b) X-direction intrusion of the front perimeter panel



(c) Peak acceleration at the bottom of column B



(d) Undominated Pareto optimal solution set

Fig. 19. Kriging approximation model error scatter plot and undominated Pareto optimal solution set

Table 6
Distribution of sample points for the 10 factors

Test number	x_1 [mm]	x_2 [mm]	x_3 [mm]	...	x_9 [mm]	x_{10} [mm]	Mass [kg]	Maximum X-direction intrusion of the front outer panel [mm]	Peak acceleration at the bottom of the B-pillar [g]
1	0.628	1.255	0.969	...	0.820	1.214	371.666	-263	-12.92
2	0.745	1.469	0.791	...	0.832	1.439	374.871	-251.3	-14.52
3	0.716	1.133	0.981	...	0.979	1.286	371.976	-259.6	-13.06
4	0.657	1.265	0.840	...	0.865	1.500	372.773	-250.6	-15.5
5	0.598	1.367	0.963	...	0.812	1.071	371.143	-266.3	-13.85
...	...	...	...	...	...	...	...	...	...
66	0.731	1.082	0.755	...	0.922	1.112	371.701	-255.1	-14.02
67	0.885	1.163	0.908	...	0.840	1.184	374.741	-261.9	-13.42
68	0.767	1.48	0.718	...	0.946	1.459	375.513	-253.9	-14.02
69	0.797	1.214	0.742	...	0.975	1.316	372.674	-259.6	-14.07
70	0.554	1.296	0.706	...	0.991	1.224	370.040	-259.4	-13.36

panel is 0.92, and the R_2 coefficient of the peak acceleration at the bottom of the B-pillar is 0.90, all of which are greater than 0.9 and meet the requirements.

The above surrogate model is solved by the non-dominated sorting genetic algorithm II (NSGA-II) algorithm. NSGA-II is a multi-objective genetic algorithm based on the concept of Pareto optimal solutions with fast non-dominated solution ordering, effective maintenance of elite and population diversity, and simple and efficient handling of constraints [26–28]. Based on referring to the literature [12, 24, 29], we selected multiple sets of a genetic algorithm-solving parameters for preliminary experiments. After fully considering the sample size, the limitations of computing resources, and the size of the optimization range, the final determined parameters are shown in Table 7, and after more than 2800 iterations, the Pareto optimal solution set is obtained as also shown in Fig. 19. The data at the blue calibration points in the Pareto frontal plane are selected as the final optimization results, and the thicknesses of the ten panels before and after optimization are shown in Table 8. A comparison of cab mass, first-order modal, and stiffness data is shown in Table 9, and the X-direction intrusion of the front perimeter panel and the peek acceleration at the bottom of the B-pillar under the frontal collision condition are shown in Figs. 20–23 and all the performances significantly improved.

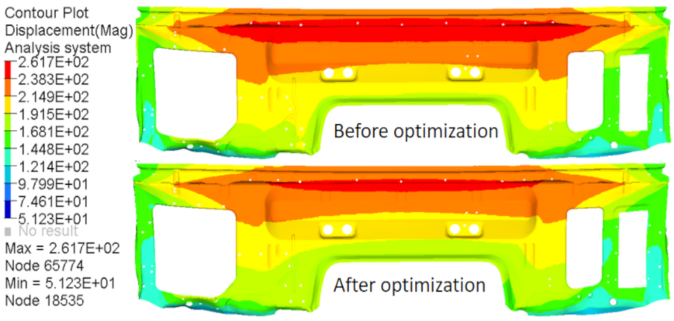


Fig. 20. Front enclosure panel intrusion

Table 7
NSGA-II solution parameters [12, 24, 29]

Parameter	Population size	Reproduction number of generations	Crossing probability	Cross-distribution index	Variability distribution index
Value	28	50	0.9	10	20

Table 8
Optimized panel thickness

Thicknesses	x_1 [mm]	x_2 [mm]	x_3 [mm]	x_4 [mm]	x_5 [mm]	x_6 [mm]	x_7 [mm]	x_8 [mm]	x_9 [mm]	x_{10} [mm]
Pre-optimization	1	1.8	1.2	2.8	3	2.0	1.2	2.0	0.9	1.2
Optimal results	0.55	1.33	0.72	2.01	3.06	2.15	1.48	2.07	0.97	1.35
Rounded results	0.6	1.4	0.7	2.0	3.1	2.1	1.5	2.1	1.0	1.4
Relative changes	–0.3	–0.4	–0.5	–0.8	+0.1	+0.1	+0.3	+0.1	+0.07	+0.15

Table 9
Optimization results

Performance	Mass [kg]	First-order modal [Hz]	Bending stiffness [N·mm^{-1}]	Torsion stiffness [N·mm·deg^{-1}]	Maximum X-direction intrusion of the front outer panel [mm]	Peek acceleration at the bottom of the B-pillar [g]
Pre-optimization	385.26	15.33	7645.16	17548.65	–262.9	–13.44
Post-optimization	372.13	15.46	7764.59	18569.56	–251.3	–12.93
Relative changes	–13.13	+0.13	+119.43	+1028.91	+12.1	+0.51

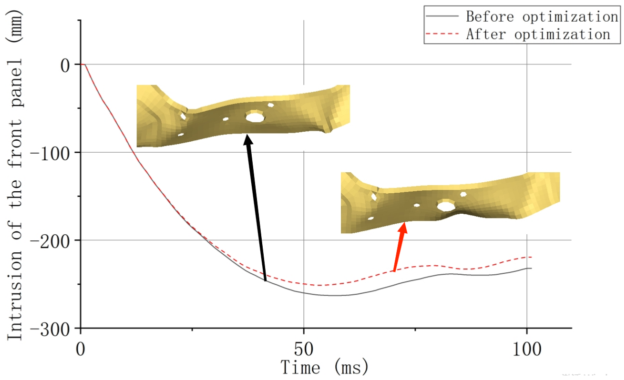


Fig. 21. Curve of front enclosure panel intrusion before and after optimization

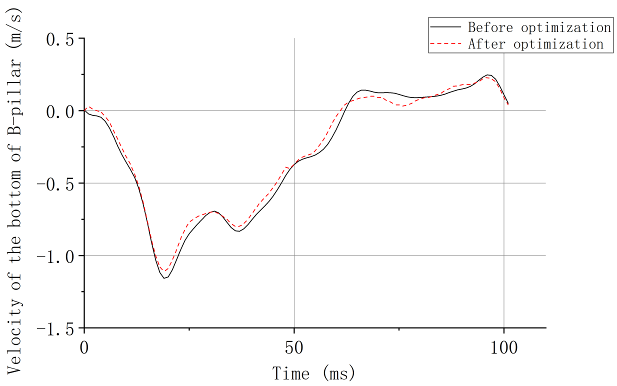


Fig. 22. Velocity curve at the bottom of the B-pillar before and after optimization

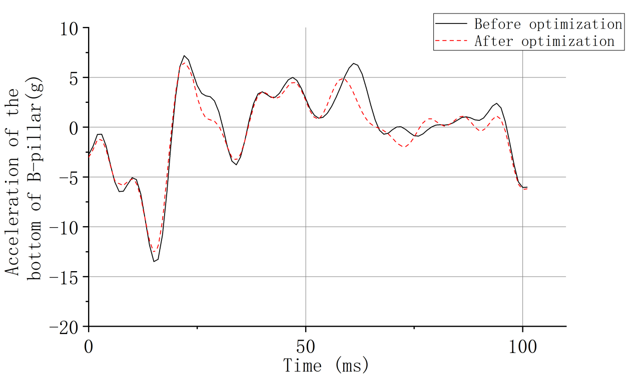


Fig. 23. Acceleration curves at the bottom of B-pillar before and after optimization

5. CONCLUSIONS

In this paper, the modal, stiffness, and strength analysis of the truck cab was carried out first, and according to GB 26512–2021, the test of four conditions of passive safety simulation of the commercial vehicle was carried out, and the static and dynamic data meet the relevant requirements, and there is a certain amount of space for lightweighting.

To address the limitations of traditional sensitivity analysis, a sensitivity hierarchical comparative analysis method is proposed with the following steps: (1) Data normalization. Using the panel thickness of truck cab components as the independent variable, the sensitivities of cab mass, first-order modal, and stiffness were calculated and data normalized to offset the dominant effect of the large order of magnitude of the sensitivities for some of the operating conditions while ensuring that the trend of the thickness effect on the performance remains unchanged. (2) Calculate the comprehensive performance sensitivity considering each working condition. The weighting coefficients are assigned to each working condition to calculate the comprehensive performance sensitivity, which integrally reflects the gradient of changes in stiffness and modal and other properties. (3) Hierarchical categorization of sensitivity. The cab mass sensitivity and comprehensive performance sensitivity are classified into equidistant categories, and the hierarchical comparative analysis of sensitivity is defined as “mass sensitivity category/comprehensive performance sensitivity category”, which is analyzed qualitatively in the form of “ratio” instead of the traditional quantitative analysis focusing on “quotient”, and the interaction between the sensitivity data and the dimension level of the components is fully considered. (4) Sensitivity hierarchy-oriented optimization strategy design. Based on the optimization requirements, the optimization matrix of the 12-dimensional sensitivity hierarchical comparative analysis method is designed in a targeted manner, the optimization priority of each component in the sensitivity analysis method is further clarified, the selection process of optimized components is perfected, and the optimization scheme is finally completed.

Based on the sensitivity hierarchical comparison analysis method, four groups of thinning components and three groups of thickening components are determined. To introduce the crash safety factors in the pre-lightweighting period, based on the deformation of the cab in the collision simulation, the analysis of the load path and the combination of the research results of previous researchers, three groups of crash-sensitive components and a total of ten groups of components are selected for thickness optimization. On this basis, 70 groups of sample points were taken in the variable space to carry out the experimental design through the optimal Latin hypercube sampling method, and the Kriging surrogate model with high fitting accuracy for nonlinear working conditions was established; with the objectives of minimizing the mass of the cab and minimizing the X-direction intrusion of the front enclosure panel in the forward crash condition, and with the constraints of stiffness, first-order modes, and X-direction acceleration at the bottom of the B-pillar in the forward crash condition greater than the original value, the NSGA-II algorithm is used to find the Pareto optimal solution set, and the optimized thicknesses of ten groups of components are finally determined. It is worth noting that the Matrix of optimization strategies for sensitivity hierarchical comparative analysis and NSGA-II solution parameters used in this article are all based on the selected cab model, and blindly applying them to other finite element models to be optimized may not have significant results.

The cab, selected from a mature model of a certain car company, has undergone a long-term optimization design before this article. Currently, the lightweight space is relatively small. This article uses the sensitivity hierarchical comparative analysis method for cab optimization, which improves performance in various aspects while achieving lightweight cab. It is verified that the first-order modal and stiffness of the optimized cab are increased, the peak intrusion of the front enclosure panel is reduced by 12.1 mm, the peak acceleration at the bottom of the B-pillar is reduced by 0.51 g, the passive safety is improved, and the weight of the optimized cab was reduced by 13.13 kg.

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