Optimization Design of Bonnet Inner Based on Pedestrian Head Protection and Stiffness Requirements

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Abstract

Pedestrian head impact with bonnet is one of the major causes for pedestrian severe injury or fatality. This paper proposes a multidisciplinary design optimization method for bonnet inner based on pedestrian head protection along with stiffness requirements. The static stiffness and headform collision procedure with regard to a particular industrial bonnet are analyzed. Parametric design and optimization analysis of this bonnet are carried out. Optimization solution significantly achieves better head protection effect under the premise of meeting the stiffness requirements, which validates the feasibility of this multidisciplinary optimization method and provides an approach for the optimal design of engine bonnet inner. This work shows the importance of a simultaneous approach of different disciplines in bonnet design.

1. Introduction

Road crashes result in millions of fatalities and injuries every year [1]. Head injuries accounted for the highest proportion of pedestrian fatalities among body injuries in fatal accidents [2]. 17.3 percent of pedestrian fatalities involving the head are caused by contact with engine bonnet [3]. These statistics demonstrates the need to lay stress on engine bonnet design of passenger cars by taking into account pedestrian head impact with bonnet to ensure pedestrian safety.

Another important concern for bonnet design is stiffness. The bonnet stiffness must meet the demands because some components within the engine compartment can often be very close to the bonnet surface [4]. There is a risk that component within the engine compartment may strike the bonnet during collision, which gives rise to increasing the danger to the pedestrian. Therefore, bonnet design not only must simply ensure pedestrian safety but also should consider the bonnet stiffness.

However, nowadays most researchers simply focus on improving pedestrian protection performance through bonnet design, while they ignore the stiffness requirements. Kalliske et al. [3] reduced the bonnet stiffness and mass by simply reducing the bonnet skin thickness to protect the pedestrian head. This research did not consider stiffness requirements while achieving its goal. Recently Teng et al. [4] introduced an optimization method for optimizing bonnet thickness with respect to pedestrian safety. On the basis of the optimization program, assessments of the torsional stiffness were performed for the optimal bonnet and the original bonnet. Through validation the bonnet with optimal thicknesses is not only pedestrian friendly but also stiff enough. These two requirements are dealt with separately and have not been integrated into bonnet design process simultaneously. There are limited existing studies that have systematically considered both bonnet stiffness and pedestrian safety with respect to bonnet design. Therefore, this paper proposes a multidisciplinary design optimization method for bonnet based on pedestrian head protection and stiffness requirements in order to solve this problem. Static stiffness requirements regard flexural and torsional thickness of the bonnet. Pedestrian safety requirements limit the HIC (Head Injury Criterion) according to GTR No. 9 (Global Technical Regulation No. 9) [5].

A finite element model of child headform is developed according to GTR No. 9. Parametric design and optimization of bonnet are carried out as to one particular engine bonnet. LS-DYNA® is used for head-to-bonnet impact simulation. MSC NASTRAN is used for stiffness analysis. SimTech ENKIBONNET is used as process automation and parametric optimization tool.

2. Establishment of Simulation Model

2.1 Headform and bonnet FE model

According to the child headform description of GTR No. 9 and its validation method, finite element model of headform is established, which is shown in Figure 1. This bonnet is made of steel, and is composed of inner structure, external skin, hinges and hinge reinforcement, whose structure is shown in Figure 2. The thickness of both inner structure and skin are 0.7mm. The outer edge of the panel is connected by flanging, whose thickness is 2.1mm. Structural glues between two panels have coincident nodes. In the bolt holes position, rigid nodes are used to simulate the connection of inner structure, hinges and hinge reinforcement. The whole FE model includes 22,733 nodes and 22,971 elements.

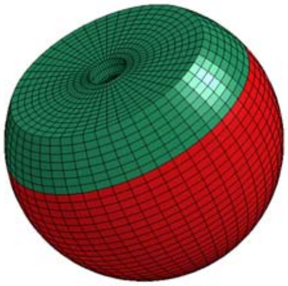


Figure 1. Headform FE model

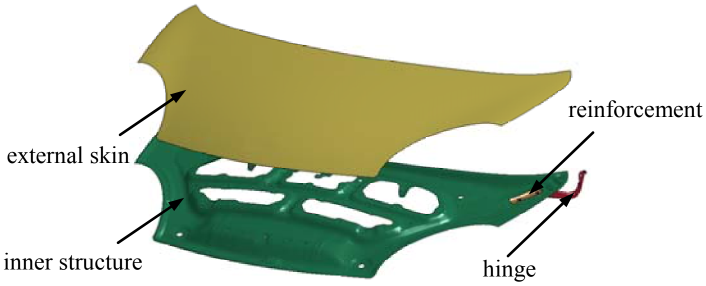


Figure 2. Bonnet structure

2.2 Pedestrian head-to-bonnet impact simulation

Imposing the FE model constraints according to the real vehicle installation conditions, i.e. hinges and lock position are fully constrained and Z axis' translation of rubber blocks on both sides are constrained. For children head impact on the bonnet, the headform is shot to the bonnet with 35km/h and 50° to the Ground Reference Level in accordance with the GTR No. 9 regulation.

The main purpose of simulation analysis is to verify the feasibility of the proposed optimization method, so one particular impact point with relatively high head injury is chosen for subsequent impact analysis and optimization design. This point is near the lock location and on the bonnet axis of symmetry, which is shown in Figure 3. The FE model does not include the underneath parts of the engine compartment due to that those stiff components inside the engine compartment could affect the performance in this test. In this way, it can better understand the real behavior of the bonnet.

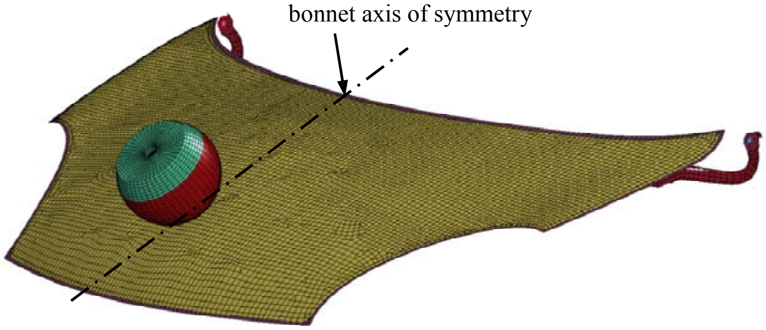


Figure 3. FE model of head-to-bonnet impact

The injury level of the pedestrian head is evaluated by means of the HIC. This parameter is calculated from the acceleration of the head's center of gravity during a head impact. The HIC parameter should not exceed a reference value of 1000 for the survival of a human [6]. The headform impactor acceleration curve of this impact point results from simulation analysis is shown in Figure 4. The HIC obtained is 1019, which has exceeded regulatory safety threshold; therefore this reference design should be improved.

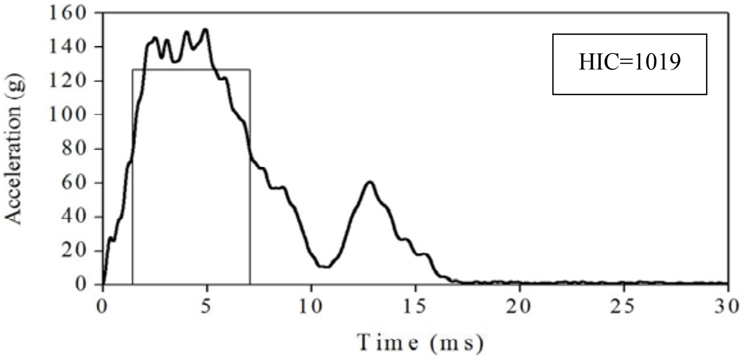
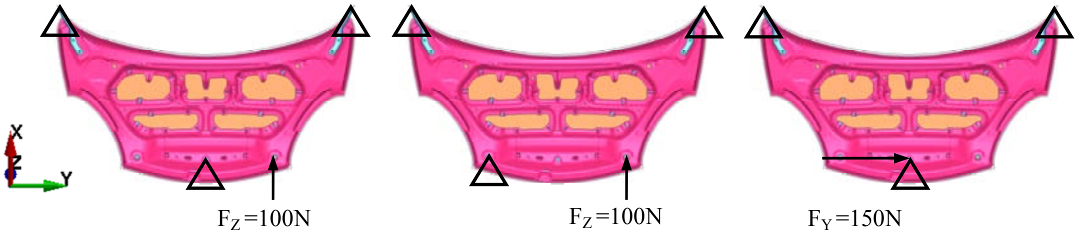


Figure 4. Head acceleration curve at impact point

2.3 Global stiffness tests

According to the stiffness test standard of one automobile company, the global stiffness of this bonnet has been evaluated by simulating three different tests, that is, two torsion tests and one lateral test, as shown in Figure 5.



(a) Torsion test 1 (b) Torsion test 2 (c) Lateral test

Figure 5. Three different global stiffness tests

Torsion test 1: DOF 123 of hinges on both sides and DOF 3 at the middle lock device are constrained, meanwhile 100N load is applied to the Z direction on the right side of rubber block.
Torsion test 2: DOF 123 of hinges on both sides and DOF 3 of rubber block on the left side are constrained, meanwhile 100N load is applied to the Z direction on the right side of rubber block.
Lateral test: DOF 123 of hinges on both sides and DOF 3 of middle lock position are constrained, meanwhile 150N load is applied to the Y direction at the lock device.
The results of the stiffness tests have been summarized in Table 1. The lateral stiffness is much larger than the reference value. Torsional stiffness 1 and torsional stiffness 2 are close to their own reference values, but still satisfy the design requirements. Therefore, the focus of subsequent stiffness analysis is whether these two torsional stiffness can meet the design requirements or not.

Table 1. Three bonnet stiffness

Stiffness tests	Torsion test 1	Torsion test 2	Lateral test
Load (N)	100	100	150
Stiffness (N/mm)	30.1	8.1	101.4
Reference value (N/mm)	25	7	60

3. Optimization Design of Inner Structure

Combined with dynamic headform impact and bonnet static stiffness analysis, this paper turns inner structure's optimization into parametric design using ENKIBONNET. Through optimization and validation, the optimal bonnet design solution is obtained.

3.1 Optimization variables

Optimization variable 1 - inner structure thickness X_1

The thickness variations of both skin and inner structure are possible, and both of them have a great influence on head injury during a collision as well as the overall bonnet stiffness. Considering simplification, this work just selects inner structure thickness as an optimization variable.

Optimization variable 2 - local shape optimization variable X_2

The external shape of the skin could not be changed because it was defined by style. For this reason, this work chooses the shape variation of inner structure as another optimization variable.
Since this inner structure has an obvious groove structure in the impact point position, structure deforming is hard to implement and head injury is high. Hence, authors consider smoothing this local inner structure in this area during optimization.
Parameterization of X_2 adopts the idea of parametric design based on CAE. Grid model can be changed directly on CAE model with this method, which avoids the cross-platform operation from CAD to CAE. This is accomplished by using the Morphing technology in ENKIBONNET. As shown in Figure 6, one local shape optimization area is selected in the inner structure, and perturbation vectors are set on each control point so as to generate deforming parameter X_2. X_2 is independent of the changes of CAD model and mesh changes within the domain is achieved by controlling the domain deformation. In other words, X_2 represents the intensity of local shape changes. X_2=0 means retain the original mesh as unchanged. Meanwhile, the larger of X_2, the greater the mesh deformation within the domain is.

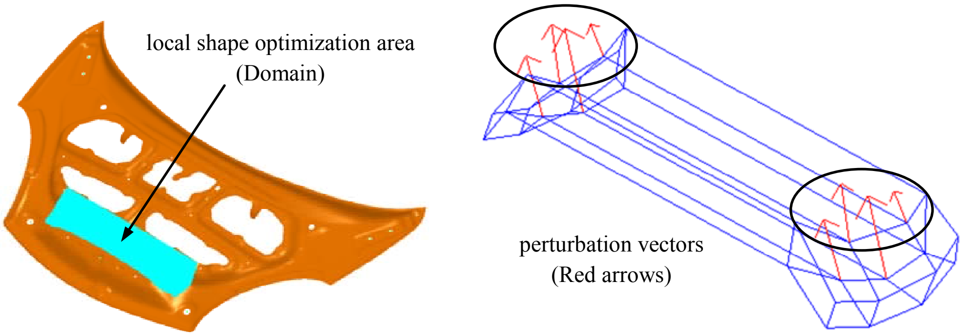


Figure 6. Local shape optimization area and its perturbation vectors

3.2 Design of optimization solution

This optimization objective is to minimize head injury at this impact point on the premise of meeting stiffness requirements.

Design variables : X=[X_1, X_2]

Objective function : The head injury criterion HIC(X) at this impact point.

Constraints: They are determined by two aspects, the head injury criterion and bonnet stiffness. The head injury criterion HIC(X) should less than 1000 to meet regulatory requirements. Moreover, the bonnet stiffness K_j(X), j=1,2,3, must be greater than their own reference values. Wherein K_1(X), K_2(X), K_3(X) represent torsion stiffness 1, torsion stiffness 2 and lateral stiffness respectively.

Thus this mathematical model of bonnet optimization can be expressed as:

$$\min\ \mathrm{HIC}(\mathrm{X}),\ \mathrm{X}=[X_1, X_2] \tag{1}$$

$$\text{s.t.}\ \mathrm{HIC}(\mathrm{X})<1000 \tag{2}$$

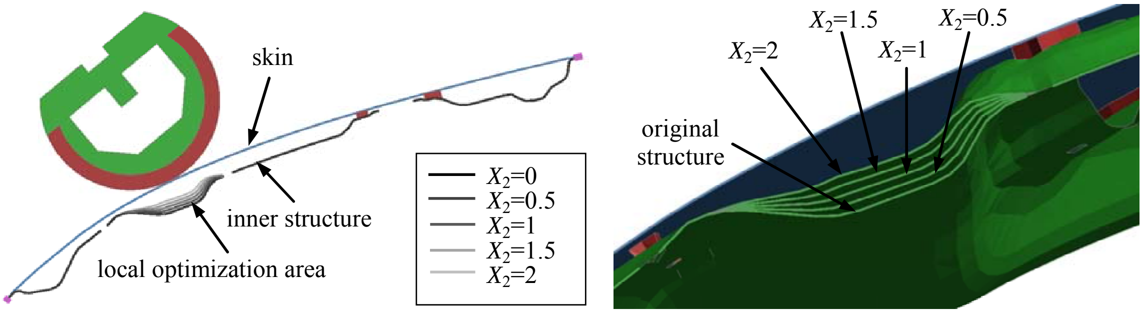
$$K_1(\mathrm{X})>25\ \mathrm{N/mm} \tag{3}$$

$$K_2(\mathrm{X})>7\ \ \mathrm{N/mm} \tag{4}$$

$$K_3(\mathrm{X})>60\ \mathrm{N/mm} \tag{5}$$

3.3 Design of experiments (DOE)

Design variable X_1 has three levels: 0.6mm, 0.7mm, 0.8mm, whilst design variable X_2 has five levels: 0, 0.5, 1, 1.5, 2, hence 15 solutions are designed through full factorial method. Section view of head-to-bonnet impact FE model along bonnet symmetry axis is shown in Figure 7. As can be seen, as X_2 increases from 0 to 2, depth of inner structure groove in this local area decreases, and the local shape is more smooth and deformable simultaneously.



(a) Inner structure section view (b) Enlarged section view

Figure 7. Different inner structures as X_2 changes

Simulation results are shown in Table 2. Without changing the shape of inner structure (i.e. X_2 remains the same), the torsional stiffness and lateral stiffness of bonnet as well as head injury increase with the increase of X_1. Therefore, in order to better improve pedestrian head safety in collision, the thickness of bonnet should be reduced as much as possible on the premise of meeting design requirements, for instance, the static stiffness. When X_2 increases with thickness of inner structure X_1 invariant, head injury criterion is reduced, both two torsional stiffness decrease, and the lateral stiffness increases. Besides, the change of inner structure shape has a great influence on the torsional stiffness and head injury, but has little impact on the lateral stiffness. The lateral stiffness among the 15 solutions are all larger than the reference value to a great extent. With respect to those two torsional stiffness, some solutions of these are within the range and others are not. In a nutshell, increasing bonnet torsional stiffness and reducing head injury contradict with each other, so much emphasis should be put on the three responses of K_1(X), K_2(X) and HIC(X) in the subsequent optimization analysis.

Table 2. Simulation results of DOE

Case	**X_1**	**X_2**	**K_1(X) (N/mm)**		**K_2(X) (N/mm)**		**K_3(X) (N/mm)**		**HIC(X)**
			Stiffness	**Reference value**	**Stiffness**	**Reference value**	**Stiffness**	**Reference value**	
1	0.6	0	24.6	25	6.9	7	80.7	60	817
2		0.5	24.0		6.7		80.7		776
3		1	23.3		6.5		80.7		727
4		1.5	22.4		6.2		80.9		694
5		2	21.5		6.0		81.5		677
6	0.7	0	30.1		8.1		101.4		1019
7		0.5	29.4		8.0		101.4		978
8		1	28.5		7.7		101.5		902
9		1.5	27.4		7.4		101.8		861
10		2	26.2		7.1		102.5		841
11	0.8	0	35.5		9.4		122.8		1251
12		0.5	34.7		9.2		122.9		1175
13		1	33.6		8.9		123.0		1107
14		1.5	32.3		8.6		123.4		1040
15		2	31.0		8.2		124.2		1026

3.4 Determination of optimal parameters

ENKIBONNET is used for parametric optimization, which combines response surface method (RSM) and genetic algorithm (GA) in its process automation.

In this work, the optimization method, i.e., RSM adopts quadratic multiple regression equation giving the relationship between design variables and responses on the basis of DOE results (shown in Table 2). The least square method is used to calculate the unknown coefficients in regression equation. The quadratic response surface regression model has the following equation:

$$\hat{y} = \alpha_0 + \sum_{i=1}^{n} \alpha_i x_i + \sum_{i=1}^{n} \alpha_{ii} x_i^2 + \sum_{j=2}^{n} \sum_{i=1}^{j-1} \alpha_{ij} x_i x_j \tag{6}$$

$$\boldsymbol{\alpha} = \left[\alpha_0, \alpha_1, \cdots, \alpha_n, \alpha_{11}, \alpha_{22}, \cdots, \alpha_{nn}, \alpha_{12}, \alpha_{23}, \cdots, \alpha_{(n-1)n} \right]^T \tag{7}$$

where $\hat{y}$ is the output variable, x_i the design variable, n the number of design variables, $\boldsymbol{\alpha}$ the vector of undetermined coefficients, which can be obtained by fitting at least squares principle. Optimal parameters are obtained under the condition of satisfying optimization design solution through the analysis of regression equation. The response surface functions of K_1(X), K_2(X), K_3(X) and *HIC(X)* through regression analysis are calculated as follows:

$$K_1\left(X\right)=-9.799+59.1x_1+1.196x_2-3.0x_1^2-0.305x_2^2-3.6x_1x_2 \quad (8)$$

$$K_2\left(X\right)=-0.746+12.7x_1+0.135x_2-0.0857x_2^2-0.7x_1x_2 \quad (9)$$

$$K_3\left(X\right)=-28.14+159.9x_1-1.432x_2+36.0x_1^2+0.448x_2^2+1.50x_1x_2 \quad (10)$$

$$HIC\left(X\right)=-32.97+899x_1+10.77x_2+880x_1^2+25.33x_2^2-223x_1x_2 \quad (11)$$

where x_1, x_2 represent the design variable X_1 and X_2 respectively. Determination coefficients and adjustment coefficients of these four response surface functions are all very close to 1, which indicates that the response surface models constructed has high fitting accuracy. GA is adopted to optimize regression functions of these four responses.

However, the response values gained from the RSM are only least squares solution, which is not always consistent with the actual system, so the model of optimal solution is submitted to simulation in order to verify the predicted results' accuracy. The results are shown in Table 3. The error between simulation results and RSM results is very small, as in the range of 2%.

Table 3. Results of RSM compared with that of simulation in the optimal solution

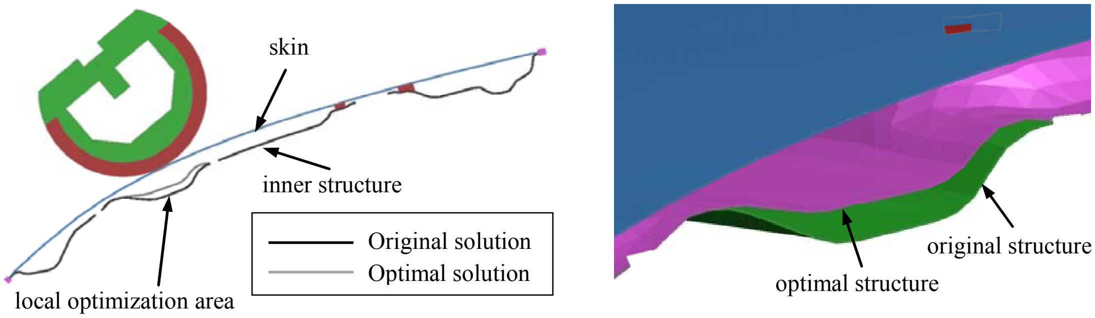
Design variables		**Compare**	**Response values**			
***X*₁**	***X*₂**		***K*₁(X)**	***K*₂(X)**	***K*₃(X)**	**HIC(X)**
0.66 mm	1.38	Simulation	25.6 N/mm	7.1 N/mm	93.1 N/mm	773
		RSM results	25.5 N/mm	7.0 N/mm	92.9 N/mm	758
		Error	0.4%	1.4%	0.2%	1.9%

3.5 Comparison of optimal solution and original solution

The results of optimal solution compared with that of original solution are shown in Table 4. The thickness of inner structure reduced from 0.7mm to 0.66mm in the optimal solution and the inner structure is optimized in the local area. Figure 8 is the comparison of inner structure section view.

Table 4. Optimal solution compared with original solution

Solution	**Design variables**		**Response values**			
	***X*₁**	***X*₂**	***K*₁(X)**	***K*₂(X)**	***K*₃(X)**	**HIC(X)**
Original solution	0.7 mm	0	30.1 N/mm	8.1 N/mm	101.4 N/mm	1019
Optimal solution	0.66 mm	1.38	25.6 N/mm	7.1 N/mm	93.1 N/mm	773
Δ（%）	-5.7	-	-15.0	-12.3	-8.2	-24.1



(a) Inner structure section view (b) Enlarged section view

Figure 8. Inner structure comparison of original and optimal solution

Improved design reduces the groove depth of inner structure in the local area and increases the contact area when head-to-bonnet impact happens at this impact point. For the reason that the inner structure is more deformable, deformation energy absorption improves efficiently. The HIC reduces 246, which meets regulatory requirements with more than 20% of safety margin. Acceleration curve comparison of these two solutions is shown in Figure 9. The peak acceleration measured in the optimal solution leads to a reduction of 14g. Compared with the original bonnet, the optimal bonnet is more pedestrian friendly but slightly less stiff than the original bonnet. Although all three global stiffness of the optimal bonnet are lower than those of the original one, they still satisfy the requirements. By comparison of these two solutions, optimization significantly improves pedestrian head safety, which validates that this multidisciplinary optimization method is feasible.

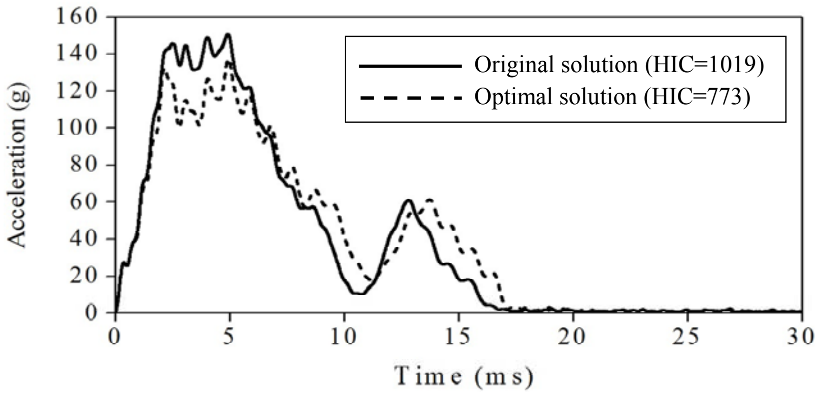


Figure 9. Acceleration curve comparison of original and optimal solution

4. Conclusions

In this work, the structure optimization of bonnet inner is turned into a parametric design process. Process automation and optimization are realized with the help of SimTech ENKIBONNET, which can couple both LS-DYNA and MSC NASTRAN solvers. Pedestrian head protection and static stiffness targets of bonnet have conflicting design requirements which currently result in design compromises. In this work, by coupling the pedestrian head protection and bonnet static stiffness analysis for the design optimization of inner structure, the optimal design obtained validates the feasibility of this multidisciplinary optimization method. The proposed method can be used to optimize other parameters to develop better designs for a pedestrian-friendly bonnet. Moreover, extending from local shape optimization of inner structure to overall optimization and applying this method to forward development and parametric design of inner structure can be further research directions.

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