Sensors and Materials, Vol. 34, No. 9 (2022) 3581–3591
MYU Tokyo

S & M 3062

Feasibility of Approximate Model Optimization for Lightweight Design of Vehicle Body Structure Based on Sequential Quadratic Programming Algorithm

Tianjun Zhu,[1*] Yang Wu,[2] Zhuang Ouyang,[3**] Tunglung Wu,[1] Jianguo Liang,[1] Weihao Li,[1] Bin Li,[4] and Shiting Han[1]

[1]Department of Mechanical and Automotive Engineering, Zhaoqing University, Zhaoqing 526021, China
[2]CATARC (Tianjin) Automotive Engineering Research Institute Co., Ltd., Tianjin 300300, China
[3]Guangdong Zhaoqing Institute of Quality Inspection & Metrology, Zhaoqing 526000, China
[4]Aptiv PLC Company, Troy 48098, USA

(Received July 4, 2022; accepted September 20, 2022)

Keywords: transfer path, experimental design, approximate model, sequential quadratic programming

The general trend in the development of the automobile industry is toward lightweight vehicles, because weight has an important role in determining the performance and quality of vehicles. The body in white (BIW) refers to the stage in automotive design or automobile manufacturing in which a car body's sheet metal components have been welded together but before the moving parts (doors, hoods, deck lids, and fenders), motor, chassis sub-assemblies, and trim (glass, seats, upholstery, electronics, etc.) have been added and before painting. In this paper, we propose an approximate model optimization for the lightweight design of the lower body structure that is based on a sequential quadratic programming algorithm. The proposed comprehensive multi-objective optimization method is used to minimize the body weight without reducing the performance, i.e., the bending and torsion stiffness of the BIW. Firstly, in the conceptual design stage of the BIW, the load transfer path of the BIW is determined using topological technology. The load transfer path is used to guide the structural design and layout of the lower vehicle body. Then, combined with implicit parametric modeling technology, the full parametric BIW model is established, and the size, position, and thickness of the cross section of the lower vehicle body are determined by a multidisciplinary optimization method, and the initial design of the vehicle body weight is reduced. Secondly, the test scheme is designed, and the approximate model of the response surface takes the bending and torsional stiffnesses and the mass of the BIW into consideration. Thirdly, the sequential quadratic programming algorithm combined with the multidisciplinary collaborative optimization algorithm is used to carry out the multi-objective optimization design of the BIW structure and obtain the Pareto optimal solution set. Our results show that the proposed method reduces the weight of the vehicle lower body by 4.07 kg.

*Corresponding author: e-mail: happy.adam2012@hotmail.com
**Corresponding author: e-mail: zzjoyz@163.com
https://doi.org/10.18494/SAM4018

ISSN 0914-4935

1. Introduction

At present, lightweight automobiles are the most popular topic among the future development trends of automobiles. Lightweight automobiles not only reduce fuel consumption, conserve energy, and reduce emission, but also have improved power performance.[1–4] The weight of the vehicle body structure can impact vehicle safety and power performance. For example, while ensuring the strength, stiffness, mode, and collision performance of the vehicle body structure, the weight of the vehicle body structure is reduced as much as possible to improve the vehicle power and safety performance. Thus, the lightweight design and optimization of the vehicle body structure play an important role in the vehicle design process.

Several studies have investigated design methods for optimizing the design of lightweight vehicle bodies. Many studies have introduced structural optimization to reduce the manufacturing cost and vehicle weight while meeting design requirements.[5–10] Lu *et al.*[11] introduced a multidisciplinary optimization design method into the performance optimization of a vehicle, taking the door crash beam and engine hood as the optimization objects, and their improvement scheme can effectively coordinate the constraint mechanism between various performances. They also verified the feasibility of the multidisciplinary design optimization method in vehicle body design. Kodiyalan *et al.*[12] studied multi-objective methods based on a genetic algorithm approach and compared the obtained optimum solutions with experimental results. Feng *et al.*[13] proposed and developed computer optimization technologies for obtaining high performance in energy absorption applications. Wang *et al.*[14] studied the bending collapse of square tubes with variable thickness. However, since the body structure of a vehicle is a complex engineering system, a comprehensive multi-objective design method to minimize the weight without reducing the basic performance is lacking and is an urgent problem to be solved.

In this paper, in accordance with the concept A surface information of the vehicle body of multi-purpose vehicles (MPVs), the topology optimization model of a vehicle body is established using HyperMesh finite element preprocessing software, and the preliminary vehicle body structure is obtained using topology optimization technology. In combination with parametric modeling and multidisciplinary optimization technology, the layout of the vehicle body structure in the concept stage is designed. In contrast to the traditional design of the vehicle body, in this paper, we propose that in the early stage of the vehicle structure design, the implicit full parametric body in white (BIW) model is adopted, and through the multidisciplinary integrated optimization design process, the optimization algorithm is used to find the optimal section size and thickness. This enables the body mass to be reduced, achieves the balance between vehicle functionality and economy, and fully excavates the vehicle body performance in the early stage of car body development, thus maximizing the potential of lightweight vehicles.

The major contributions of this paper are summarized as follows:

1. We design a multi-objective optimization approach based on a sequential quadratic programming algorithm to find the optimal section size and thickness, so as to reduce the body mass without reducing the basic performance.
2. The proposed lightweight design method is applied to the BIW development of an MPV, and the weight of the body is reduced from 425.69 to 421.62 kg, a weight reduction of 4.07 kg.

2. Topological Optimization Model

In the early development stage of a car body, when there are only CAS and layout requirements, to decide how to distribute the transverse beam of the body structure, the vehicle body topology space is optimized to find the load transfer path of the vehicle body by considering the bending and torsional stiffnesses and the collision conditions. Then, the layout plan of the first version of the vehicle body structure and the cross longitudinal beam of the vehicle lower body is established by combining the topology path. According to the layout plan, the finite element model is established, and implicit parametric modeling technology is used to parameterize the current layout scheme. Finally, the parameterized body is optimized by employing optimization technology to find the appropriate body structure and layout while meeting the body performance requirements.[15]

The load transfer path analysis uses topological optimization technology to establish the topological optimization space of an MPV BIW with information such as the general layout as the input conditions, as shown in Fig. 1.

Figure 2 shows the topological optimization results of the BIW calculated with the bending and torsional stiffnesses as the objective. Subsequently, the path is interpreted in accordance with the topological results. After the position of the cross longitudinal beam of the lower car body is determined, finite element modeling is carried out, and parametric modeling is carried out using the finite element model.

3. Parametric Model

The lower car body structure is set as shown in Fig. 3 on the basis of the topology optimization structure using the input of the general layout, modeling, chassis, power, the area of the interior and exterior decoration, and so forth, while comprehensively considering the balance of each area.[16] The structure of the vehicle lower body and the layout position of the cross beam are interpreted as shown in Fig. 3.

As shown in Fig. 4, the wireframe model is established according to the interpreted lower car body model. This model mainly describes the position of the cross beam and other information

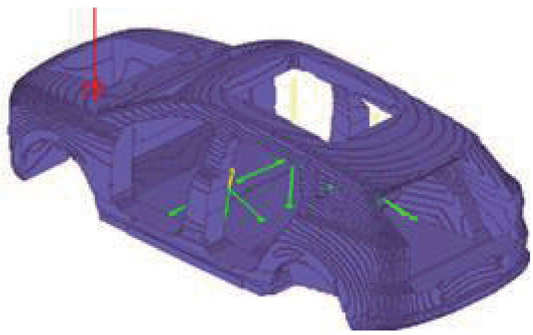

Fig. 1. (Color online) Definition of topology optimization space.

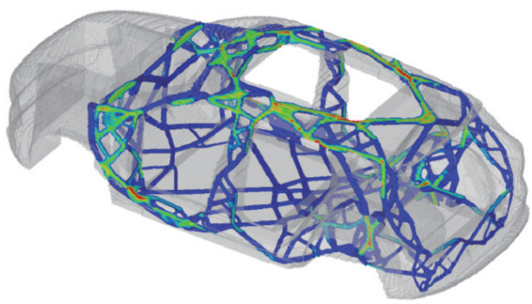

Fig. 2. (Color online) Topology optimization results of BIW.

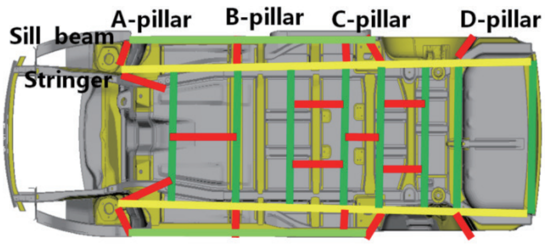

Fig. 3. (Color online) Initial lower body structure.

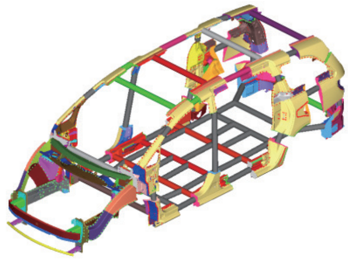

Fig. 4. (Color online) Wireframe model of lower body.

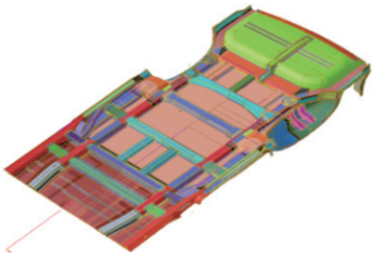

Fig. 5. (Color online) Parametric model of BIW lower vehicle body.

Fig. 6. (Color online) BIW stiffness test.

of the lower car body. The section size and thickness and other information are required to establish a complete CAD model. The CAD model is divided into finite element meshes, and then the divided finite element model is parameterized. After the parameterized modeling, the position of the cross beam of the lower car body can be determined, where the interface size, thickness, and other variables are taken and optimized on the basis of the selected variables.

Figure 5 shows that the finite element model is established on the basis of the topological model, and the parametric model is established according to the established finite element model. Then, the structural design and optimization of the lower body are carried out on the basis of the parametric model.

Figure 6 shows the bending and torsional stiffness test of an actual vehicle model that is constructed from the optimized design.

As shown in Fig. 6, sensors are arranged on the sill beam and the tower package to measure their displacements to determine the bending and torsional stiffnesses. The sensors arranged on the sill beam mainly measure the displacement after the vehicle body is stressed. Figure 7 shows the underbody, along with the sensors arranged on the sill beam and the front and rear longitudinal beams.

The vehicle coordinate system is defined as follows: the forward direction is the positive direction of the x-axis, the left side of the forward direction is the positive direction of the y-axis, and the vertical direction is the positive direction of the z-axis. The x-, y-, and z-coordinates conform to the right-hand rule. The locations of measuring points depend on the specific

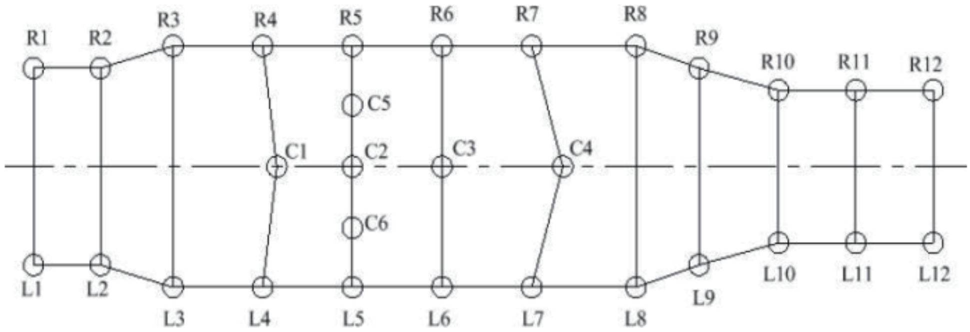

Fig. 7. Arrangement of measuring points of BIW.

structure of the vehicle body. Generally, the measuring points are set on the main structural parts of the vehicle body, and a sensor is placed at each measuring point. Measuring points include the front longitudinal beam, sill beam, transmission shaft channel, and rear longitudinal beam. The number of measuring points on each beam depends on the length of the beam and the connection mode of the structure. The total number is generally 40–50 and the spacing between them is generally 300–350 mm, as shown in Fig. 7.

4. Experiment Design

After setting the variables of the model according to the established parametric model, the experiment design is carried out. The test sampling level depends on the number of variables and their levels. Through adjusting parameters such as the cross section, thickness, and spatial position of the beam of the BIW, the structure of the BIW can be changed. Sample points are generated by the optimized Latin square sampling technique. The Latin square algorithm is used to ensure that all the test points are as evenly distributed as possible in the design space, with very good space filling and balance. In this paper, a total of 27 cross girders with cross sections, positions, and thicknesses are selected as design variables. In the design of the experiment (DOE), 30 variable parameters are selected for the experiment design, generating 60 groups of variable combinations, i.e., combinations of the cross section, position, and thickness of the lower body beam.

Figure 8 shows the detailed structure of the lower body of the BIW. The lower body is composed of 27 sheet metal beams. The thickness, position, and shape of each beam are design variables. In Fig. 9, the lower body beam structure is shown separately. The cross section of the lower body beam of the BIW is obtained by cutting along the middle anatomical line. Many different designs can be obtained by adopting different combinations of variables such as the thickness, cross-sectional shape, and position of the BIW sheet metal. The software can calculate the bending and torsional stiffness of the BIW by calculating different combined variables, The mass of the vehicle body is solved for different combinations, and the calculated stiffnesses and masses are compared to determine a group of optimal solutions. In the analysis and calculation, the lightweight constraint equation is as follows:

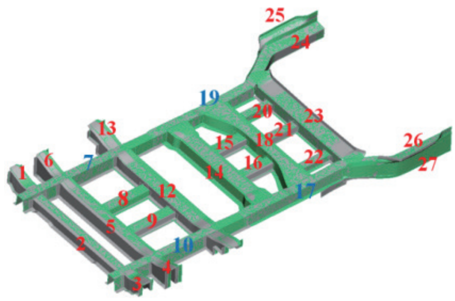

Fig. 8. (Color online) Longitudinal and lateral beams of lower vehicle body.

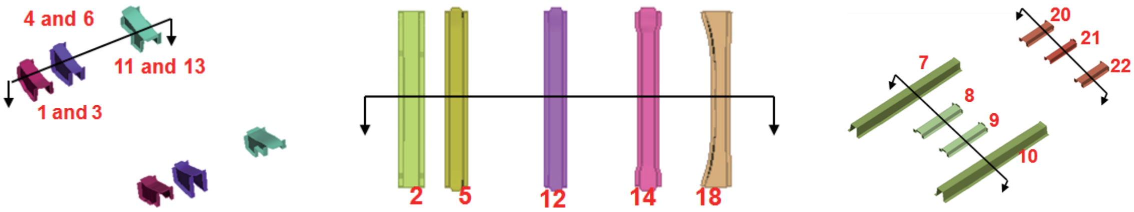

Fig. 9. (Color online) Cross sections of lower body cross beam.

$$\begin{cases} \min f_0(x_{(i)}) = \{f_1(x_1), \cdots, f_i(x_i)\}^T, \\ f_T(x_{(i)}) \geq b_{k1}, k_1 = 1, 2, 3, \cdots, \\ f_B(x_{(i)}) \geq b_{k2}, k_2 = 1, 2, 3, \cdots, \\ x_L \leq x_i \leq x_U, i = 1, 2, \cdots, n. \end{cases} \tag{1}$$

Here, f_0 is the objective function, that is, the mass of the BIW to be minimized; f_T is the function of the constraint variable of torsional stiffness; f_B is the function constraint variable of bending stiffness; b_{k2} and b_{k1} are the constraint variable values, i.e., the initial bending and torsional stiffnesses, respectively; x_i are the initial values of the design variables, including the size, position, and thickness of the beam section; x_L is the lower limit of the design variable; x_U is the upper limit of the design variable.

Using the constraint formula, reasonable changes in the beam section shape, position, and plate thickness of parts are determined, the bending and torsional stiffnesses of the body are calculated, and then an approximate model based on the data is established and then optimized.[17]

As shown in Fig. 10, in the DOE experiment design process established in ISIGHT software based on the constraint formula, the constraint variables are changed continuously. NASTRAN finite element commercial software is used to calculate each set of generated models and obtain 70 sets of data.

In this paper, the number of design variables is 30. By processing the sampling points after the completion of the experiment design, the output response values (60 groups of sample points of bending and torsion stiffnesses) are obtained. By combining the input design variables and

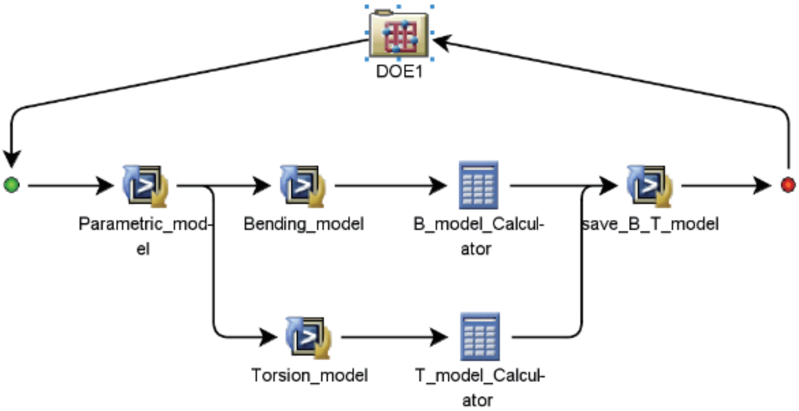

Fig. 10. (Color online) ISIGHT_DOE experiment design process.

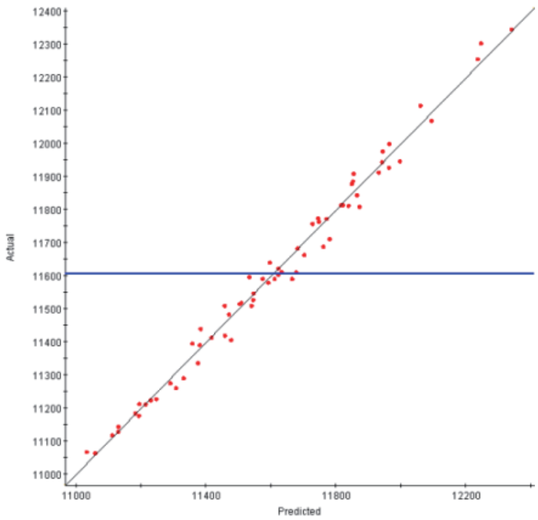

Fig. 11. (Color online) Approximate model of torsional stiffness.

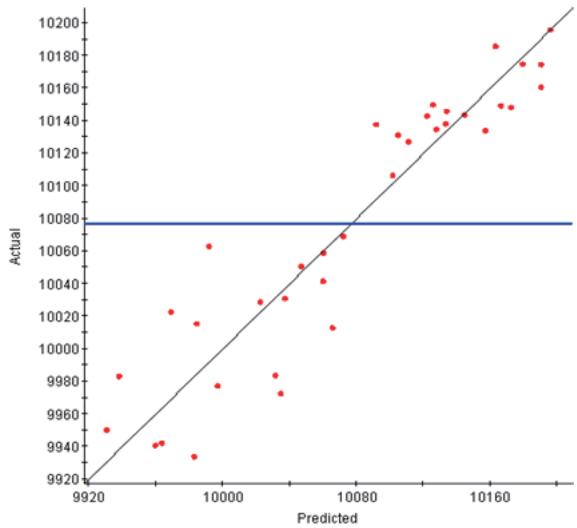

Fig. 12. (Color online) Approximate model of bending stiffness.

output response, the response surface structure functions are established, as shown in Figs. 11 and 12, where the values on the abscissa are calculated using the approximate function constructed by the software and the values on the ordinate are the actual simulation values of the original model before the optimization.

Figure 11 is an approximate model of torsional stiffness and Fig. 12 is an approximate model of bending stiffness. Then, on the basis of the approximate models, the sequential quadratic programming method is used for multi-objective optimization to obtain the sizes and thicknesses of the longitudinal and lateral beam sections.

5. Multi-objective Optimization Based on Sequential Quadratic Programming

The approximate model method is a means of approximating a group of input variables (independent variables) and output variables (response variables) through mathematical models.

Obtaining the approximate relationship can increase the speed of an optimization algorithm.[18]

The approximate model assumes that the response y depends on the variable x, and its response surface fitting function is

$$y = y(x) + \delta = \sum_{i=1}^{n} \alpha_i \phi_i(x) + \phi, \tag{2}$$

where $y = \sum_{i=1}^{n} \alpha_i \phi_i(x)$ is the expression of the response surface; n is the number of terms of the base function $\varphi(x)$; α_i is the coefficient of the base function; ϕ is the error of the response surface function.

The response surface function can be expressed as

$$\tilde{y} = a_0 + \sum_{i=1}^{m} a_i x_i + \sum_{i=1}^{m} a_{ii} x_i^2 + \sum_{i=1}^{m-1} \sum_{j=j+1}^{m} a_{ij} x_i x_j \ , \tag{3}$$

where m is the number of design variables.

In this paper, the number of design variables is 30, the minimum number of sample points is 31, and the actual number of sample points is 60, which is sufficient to construct the response surface. Thirty design variables of the underbody in the BIW are used as the input, with the bending and torsion stiffnesses as constraints and the mass as the output. ISIGHT uses NASTRAN to calculate the 60 groups of variable models for analysis and uses the results to establish an approximate model. Figure 13 shows the optimization process of the approximate model.

The approximate model function is established as a spreadsheet in Excel. The first column of the spreadsheet lists 30 design variables, and the second column lists the bending and torsion stiffnesses and the mass of the BIW. By changing the values of the design variables, the output changes accordingly. The approximate model is optimized by ISIGHT software, which uses sequential quadratic programming (SQP) to find the compromise solution set satisfying the constraint by the gradient search method. Considering the number of variables and the amount of calculation, 60 sample points and a first-order response surface are used for data fitting. The accuracy level is above 0.9, which meets the accuracy requirements of the approximate model.

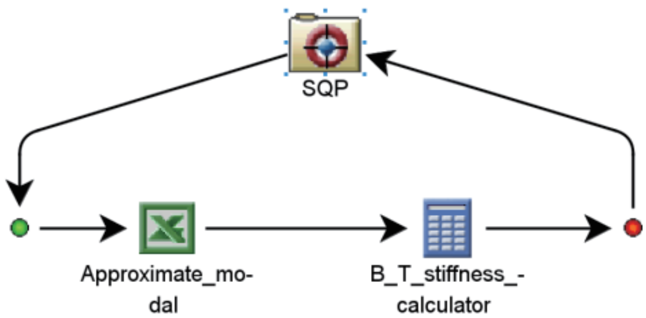

Fig. 13. (Color online) SQP optimization process.

Table 1 gives the final optimization results obtained using SQP in ISIGHT software, taking the current performance level as the constraint and the minimum quality as the optimization objective. The section size is given in Fig. 14.

Table 1
Thickness of lower vehicle body.

Number	Thickness (mm)				Number	Thickness (mm)			
	Initial	Scheme 1	Scheme 2	Scheme 3		Initial	Scheme 1	Scheme 2	Scheme 3
1	1.2	0.8	0.8	0.9	15	1.5	1.1	1.1	1.3
2	1.2	0.8	0.8	0.8	16	1.5	1.1	1.1	1.3
3	1.2	0.8	0.8	0.9	17	1.8	2.4	2.4	2.4
4	1.5	1.1	1.1	1.2	18	1.2	0.8	1.8	1.4
5	1.4	1	1	1	19	1.8	2.4	2.4	2.4
6	1.5	1.1	1.1	1.2	20	1.5	1.1	1.1	1.2
7	1.8	1.4	1.4	1.4	21	1.5	1.1	1.1	1.6
8	1.5	1.1	1.1	1.1	22	1.5	1.1	1.1	1.2
9	1.5	1.1	1.1	1.1	23	1.4	1	1.0	1.4
10	1.8	1.4	1.4	1.4	24	1.8	2.4	2.4	2.4
11	1.5	1.1	1.1	1.2	25	1.8	1.2	2.1	2
12	1.2	0.8	0.8	0.9	26	1.5	2.4	2.4	2.4
13	1.5	1.1	1.1	1.2	27	1.5	1.2	2.1	2
14	1.2	1.8	1.8	1.8					

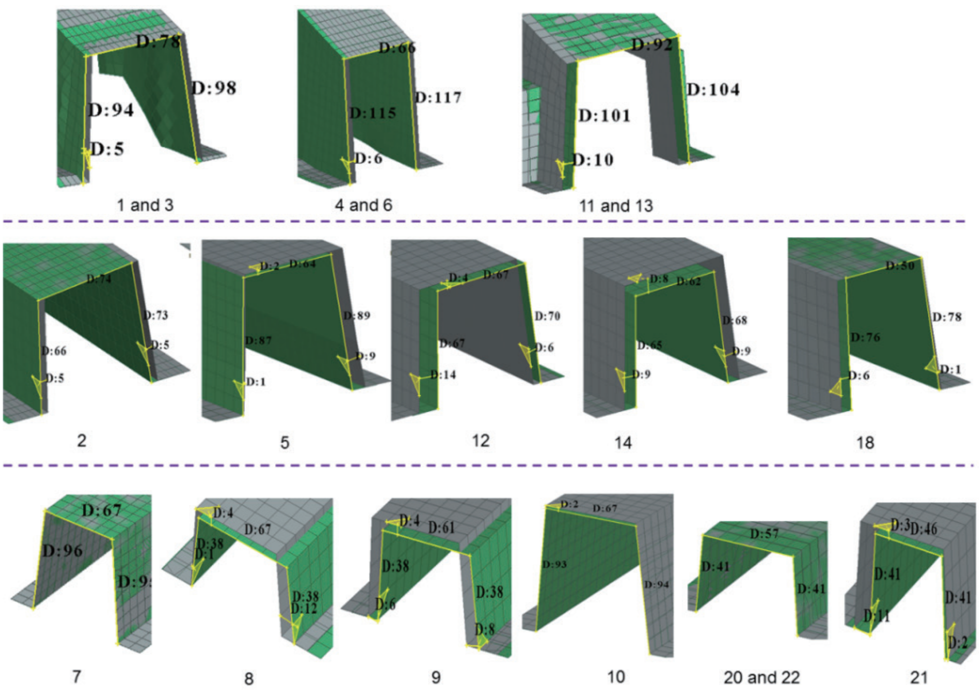

Fig. 14. (Color online) Different sectional sizes of longitudinal and lateral beams after optimization.

Table 2
Comparison of bending and torsion stiffnesses and mass of lower vehicle body for different optimization schemes.

Plan	Torsion_stiffness (N.m/deg)	Bending_stiffness （N/mm）	Mass/（kg）	Remarks
Initial	10769	9948	425.69	Benchmark performance.
Scheme 1	10724	10378	421.62	When performance is basically unchanged, carry out feasible weight reduction.
Scheme 2	9290	8976	410.53	Performance cannot be met only by considering weight reduction.
Scheme 3	11381	11141	426.60	Performance is improved and the mass is increased.

In Table 1, the data in the second column are the 27 initial sheet metal thicknesses of the vehicle body, and the data in the third, fourth, and fifth columns are the 27 sheet metal thicknesses after software optimization for Schemes 1–3 (see below), respectively.

Because the implicit parametric model has a fully parametric function, the position, shape, and thickness of the geometry can be changed arbitrarily. The software can record the thickness, position, and shape of sheet metal changes and convert them into design variables. Therefore, based on this model, the section size of components can be taken as the optimization variable, and the size of each component can be analyzed to determine the optimal section size. Figure 14 shows the section size and shape of the longitudinal and lateral beams at different positions after optimization. The initial beam (gray part) can be compared with the optimized cross beam (green part). The sizes in the figure are measured using the gray part as the benchmark, and the difference between the section shapes before and after optimization can be clearly seen.

Table 2 shows three schemes. In Scheme 1, the performance of the car body is basically unchanged and feasible weight reduction is carried out, then the thickness, the bending and torsion stiffnesses, and the mass of the lower vehicle body are calculated. In Scheme 2, the weight reduction is considered but the performance is not considered, and the thickness, the bending and torsion stiffnesses, and the mass of the lower vehicle body are calculated. In Scheme 3, the performance is the major consideration. The thickness, the bending and torsion stiffnesses, and the mass of the lower vehicle body are calculated as the weight is increased.

Each of the three optimization schemes has a different purpose. In the conceptual design stage, the weight can be reduced by comprehensive consideration while satisfying the performance, or the position and section size of the beam can be fixed. In the detailed design stage, fine adjustment can be made to the body sheet metal section size, stiffener design, sheet metal thickness, and sheet metal material.

6. Conclusions

(1) It is concluded that topology optimization technology can be used in the early stage of body design to provide design guidance for design engineers. Also, when no car body data is available, an implicit parametric model can be established using parametric software, and the layout can be changed from an idea to an actual model. Then, the body performance is improved by structural replacement, and a lightweight body is realized by optimizing the section size and thickness.

(2) In this study, a method for designing lightweight vehicles is applied to the BIW development of an MPV, which reduced the weight of the body by 4.07 kg from 425.69 to 421.62 kg. The results show that this design method can be used for the BIW development of an MPV.
(3) Because of the large number of variables involved and the long calculation time, the approximate model can be fitted with an ith-order response surface owing to the linear relationship between the bending and torsion stiffnesses, the mass change, and the thickness. If the collision condition is also introduced into the multidisciplinary optimization of the BIW because of the material nonlinearity and other factors, when the approximate model is created, a higher-order function is needed to fit the data. Therefore, a radial basis function neural network model would be required.

Acknowledgments

This work was supported in part by the Teaching Quality and Reform of Higher Vocational Education Project of Guangdong Province (GDJG2019463), the Characteristic Innovation Project of Guangdong Provincial Department of Education (2019KTSCX201), the Hebei Province Key R&D Project (17394501D), Zhaoqing Research and Development Technology and Application of Energy Conservation and Environmental Protection Ecological Governance (2020SN004), the Quality Engineering Project of Zhaoqing University (ZLGC202034), Special Projects in Key Fields of Colleges and Universities of Guangdong Province (New Generation Information Technology: 2021ZDZX1061), and Characteristic Innovation Projects of Ordinary Colleges and Universities in Guangdong Province (2022KTSCX146).

Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

1 H. Li, Z. Liu, and P. Zhu: P . J. Mech. Sci. Technol. **35** (2021) 2073.
2 K. Yang, Y. Wang, and K. Fu: Adv. Mater. Sci. Eng. **56** (2021) 1.
3 Y. Zhang, Y. Shan, X. Liu, and T. He: Struct. Mulitidiscipl. Optim. **10** (2021) 1.
4 J. Long, F. Lan, and J. Chen: Chin. J. Mech. Eng. **44** (2008) 27.
5 H. Liao, L. Xu, and A. Cheng: Automob. Technol. **3** (2011) 15.
6 F. Pan and P. Zhu: J. Mech. Eng. **47** (2011) 82.
7 K. Morteza, G. Imtiaz, and R. Masoud: J. Magnes. Alloy **2** (2014) 99.
8 G. Zhu, A. Cheng, and Z. Wang: J. Mech. Eng. **52** (2016) 145.
9 H. Xie, P. Wang, and H. Wang: J. Plast. Eng. **25** (2018) 1.
10 H. Hu and Z. Zhong: Automot. Eng. **40** (2018) 918.
11 T. Lu, D. Wang, and C. Wang: Automot. Eng. **40** (2018) 912.
12 S. Kodiyalan, R. Yang, and L. Gu: Struct. Multidiscipl. Optim. **26** (2004) 256.
13 X. Feng, D. Wang, and S. Chen: Struct. Multidiscipl. Optim. **58** (2018) 1823.
14 Z . Wang, Q. Zhou, and K. Liu: Chin. Mech. Eng. **29** (2018) 75.
15 P. Zhu, Y. Zhang, and L. Ge: Chin. J. Mech. Eng. **41** (2005) 207.
16 T. Y. Chen and S. C. Wu: Comput. Mech. **21** (1998) 483.
17 R. T. Marler and J. S. Arora: Struct. Multidiscipl. Optim. **26** (2004) 369.
18 C. Wang, D. Wang, and S. Zhang: Proc. IMechE Part D: J. Autom. Eng. **230** (2016) 273.