Multidisciplinary Design Optimization of Crash Box with Negative Poisson's Ratio Structure

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Abstract: To improve the crashworthiness and energy absorption performance, a novel crash box negative Poisson's ratio (NPR) structure is proposed according to the characteristics of low speed collision of bumper system. Taking the peak collision force and the average collision force as two subsystems, a multidisciplinary collaborative optimization design is carried out, and its optimization results are compared with the ones optimized by NSGA-II algorithm. Simulation results show that the crashworthiness and energy absorption performance of the novel crash box is improved effectively based on the multidisciplinary optimization method.

Key words: crash box; multidisciplinary optimization; negative Poisson's ratio; energy absorption; low-speed collision

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0 Introduction

In a low-speed collision, the bumper system and its energy-absorbing parts can absorb the impact energy caused by the collision[1]. As the main energy absorption component of the anti-collision system, the crash box can absorb most of the energy in a short time, and protect the safety of drivers and passengers.

Owing to the great effect of crash box on the passive safety, many researches have been done to improve its energy absorption performance. Li et al.[2] found that increasing the wall thickness properly could improve the energy absorption characteristics of the crash box. However, the wall thickness of the energy absorption box would lead to excessive peak collision force and damage the car body. Liu et al.[3] enhanced the performance of the crash box through the multi-objective optimization design of the position and depth. Lan et al.[4] compared and analyzed the energy absorption characteristics of the crash box filled with aluminum foam. They found that the crash box filled with aluminum foam not only could greatly improve the energy absorption capacity, but also had stronger stability in the process of compression and deformation.

In order to further improve the crashworthiness and energy absorption performance, the negative Poisson's ratio (NPR) structural material was used to the crash box[5-7]. The research results showed that the NPR crash box could ensure that the system absorb more collision energy during the collision process and improve the collision performance. For the sake of the improvement of crashworthiness performance, some single- and multi-objective optimization algorithms have been used to optimize the structures of crash boxes. However, there is a coupling effect between the optimization objectives of crash boxes. The simple weighting method is difficult to consider the mutual influence and coupling relationship among the objectives. In this case, the final optimization result is rarely the global optimal

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solution of the energy absorption system. Therefore, this work conducts the multidisciplinary optimization of the NPR crash box to improve the system's crashworthiness and energy absorption performance.

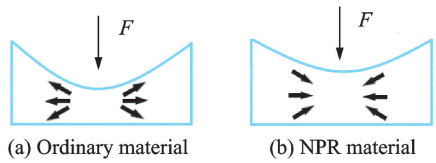

Fig.1 Deformation characteristics of NPR structure

1 Modeling of NPR Unicellular Structure

The Poisson's ratio is defined as a ratio of the transverse strain to the longitudinal strain. As shown in Fig.1, the NPR effect refers to the transverse expansion change of the material within the elastic range when the tensile stress is received. On the contrary, the transverse contraction of the material changes when it is compressed.

In this paper, the new crash box is established on the basis of a traditional one, which is composed of two parts connected by welding. Its structure size is 235 mm in length, 120 mm in width and 62 mm in height. Based on this, a NPR inner core is designed to fill into the traditional part shell, and its cellular model is shown in Fig.2. This structure has been proved with good NPR characteristics[8-9]. As shown in Fig. 2, the unicellular structure is determined by four main variables: The base length a, the hypotenuse length b, the angle θ and the thickness t. Through Hypermesh software, the finite element model of the inner core is established, and it contains 52 578 quadrilateral grid elements and 70 536 nodes. The main modeling process is shown in Fig.3.

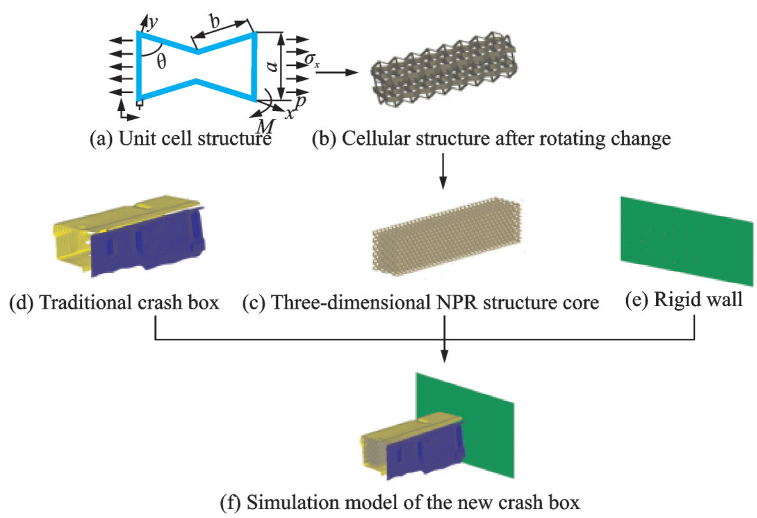

Fig.2 Modeling process of the new crash box

The Ls-Dyna software is applied to simulate the collision process. In the simulation, the rigid wall is set as 900 kg, and it impacts the other end of crash box at the speed of 15 km/h. The rigid wall model is built by means of the keyword * RIGIDWALL_PLANAR. The whole time of the collision simulation is set to 80 ms and the time step is set to 1e−6 s. The finite element model of the inner core is mainly composed of quadrilateral meshes with the size of 2 mm×2 mm. In addition, both the static friction coefficient and the dynamic friction coefficient are set as 0.2.

Energy conservation is an important criterion to verify the correctness and reliability of the established model. In the collision simulation, it is necessary to ensure that the hourglass energy cannot exceed 5% of the total energy. Fig.4 shows the energy change curve of new NPR crash box. It can be seen from Fig.4 that the total energy is conserved and the hourglass energy accounts for less than 10% and 5% of the internal energy and the total energy respectively. Therefore, the established model of new crash box is accurate and can be used for subsequent optimization design.

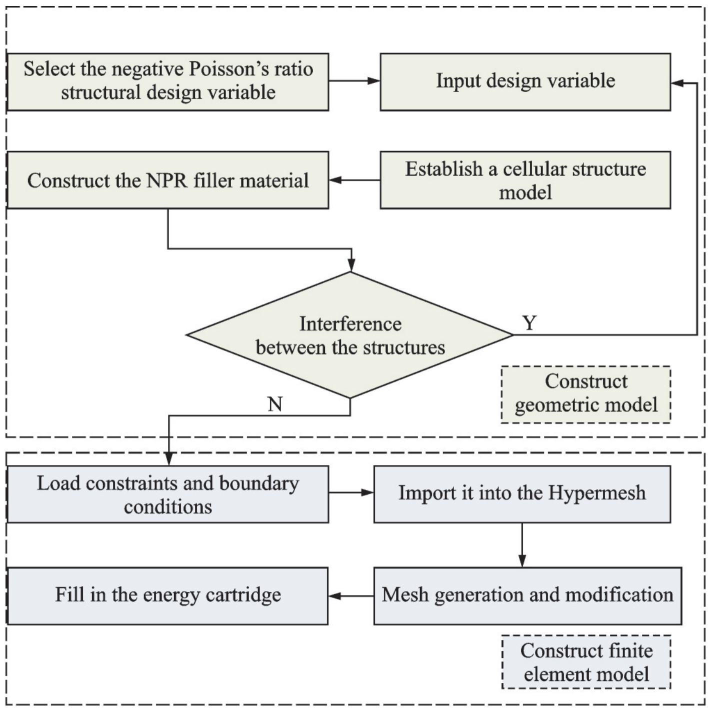

Fig.3 Overall modeling process

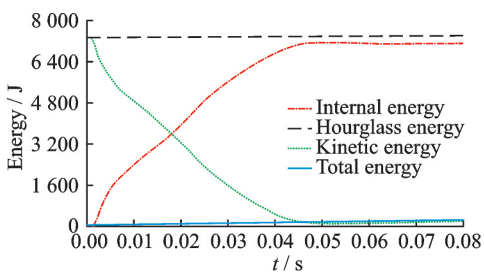

Fig.4 Energy change curves of new NPR crash box

2 Multidisciplinary Optimization Design

In this section, the multidisciplinary optimization design is conducted for the new crash box. The energy absorption E_{SEA}, the peak collision force F_{PCF}, and the average collision force F_{av} are selected as the evaluation indexes. The specific energy absorption E_{SEA} refers to the energy absorbed by per unit mass, which can characterize the energy absorption characteristics of the crash box. The peak collision force F_{PCF} is the maximum collision force of the crash box in the collision process. Moreover, the average collision force F_{av} reflects the average energy absorption level of the crash box[10].

The framework of the multidisciplinary optimization is shown in Fig.5. Firstly, the optimal Latin hypercube design is used to obtain the sample points in the range of design variables, and models are established and simulated according to the sample points. Secondly, based on the simulation results, response surface models (RSMs)[11] are established to optimize the objectives and constraints. Finally, the multidisciplinary optimization algorithm and multi-objective optimization algorithm are applied to optimize the parameters, respectively.

In the optimization, the structural parameters of the cellular NPR structure model are selected as the optimization variables. The included angle θ between the horizontal cell rib and the inclined cell rib, the length of the horizontal cell rib a, the length of the inclined cell rib b, and the cell wall thickness t are set as the design variables. The ranges of the structural size parameters are shown in Table 1.

In the multidisciplinary optimization, the collaborative optimization (CO) multidisciplinary algorithm is used for the NPR crash box. The specific energy absorption is set as the primary system, and the peak impact force and average impact force are set as two subsystems. The response surface model of performance objectives and constraints can be presented as follows.

The RSM of peak impact force F_{PCF} can be given as

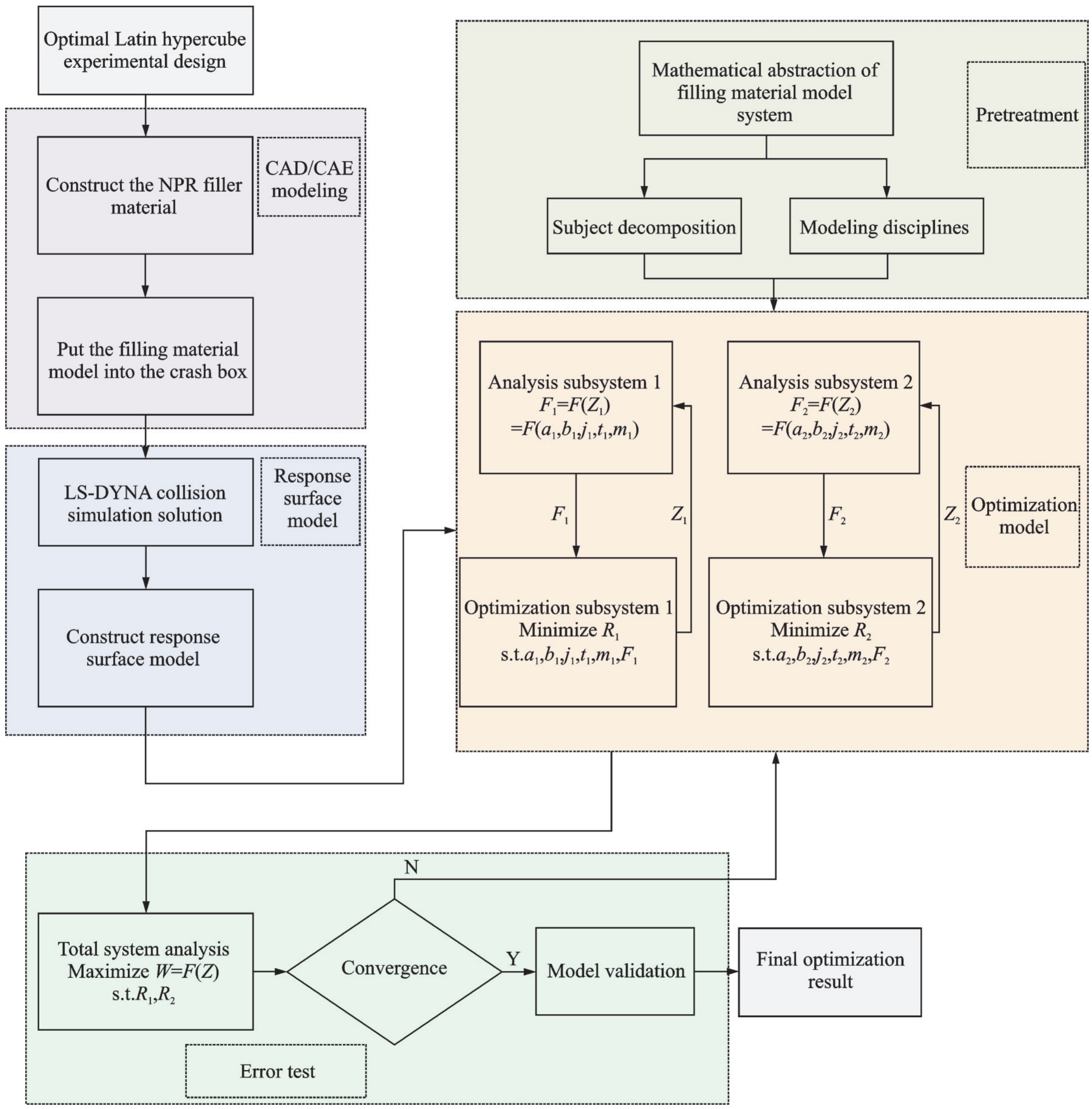

Fig.5 Framework of the multidisciplinary optimization

Table 1 Value range of optimization design variables

Design variable	Initial design value	Variable lower limit	Variable upper limit
a/mm	12.873	12	16
b/ mm	4.449	4	6
θ/ (°)	58.67	55	75
t/mm	0.776	0.5	1

$$F_{PCF}=118\,935.1-1\,183.8\theta-78\,583.5t-300.9a^2-1\,342.6b^2+560.6ab+3\,775.9am+80.4b\theta+1\,196\theta t \tag{1}$$

The RSM of specific energy absorption E_{SEA} can be expressed as

$$E_{SEA}=2\,514\,946.1+409\,168.1b+3\,454\,355.7m+366.5\theta^2-1\,175\,137.4m^2-3\,607.6b\theta-244\,886bt+17\,430.1\theta t-26\,026\theta m \tag{2}$$

The RSM of specific energy absorption F_{av} can be expressed as

$$F_{av}=273.3+9.58a-64.04b-7.749j-45.48t+168.3m-0.759a^2-1.483b^2+0.017\,7j^2-41.838t^2-207.797m^2+0.418ab+0.059\,8aj-1.727at+4.089am+0.023bj-17.976bt+50.21bm+0.198jt+2.543jm+123.27tm \tag{3}$$

In general, it is expected that the specific energy absorption E_{SEA} can be maximized on the premise of satisfying conditions. Based on the CO algorithm, the optimization model of the primary system E_{SEA} can be expressed as

$$\begin{cases}\text{Maximize} P = E_{SEA}(Z) = F(a, b, \theta, t, m) \\ \text{s.t.} R_1 \leqslant \varepsilon, R_2 \leqslant \varepsilon\end{cases} \tag{4}$$

where R_1 and R_2 are the constraints of two disciplines and ε is the relaxation factor with the value of 0.1.

In the collision process, it is generally required that the peak value of collision force F_{PCF} should be within the permissible range. Furthermore, in order to make the crash box absorb the energy as much as possible, F_{av} is expected to increase as much as possible within a reasonable range. In this paper, the peak collision force F_{PCF} and the average collision force F_{av} are selected as two subsystems. The normalization of each subsystem can make the objective function converge quickly.

The optimized model of peak collision force subsystem can be expressed as

$$\begin{cases}\text{Minimize} F_{PCF}(Z) = F(a, b, \theta, t, m) \\ R_1 = (1 - a/a_1)^2 + (1 - b/b_1)^2 + \\ \qquad (1 - \theta/\theta_1)^2 + (1 - t/t_1)^2 + (1 - m/m_1)^2 \\ 12 < a_1 < 16, 4 < b_1 < 6, 55 < \theta_1 < 75, \\ \qquad 0.5 < t_1 < 1.0, 1.6 < m_1 < 1.8\end{cases} \tag{5}$$

The optimized model of average collision force subsystem can be depicted as

$$\begin{cases}\text{Maximize} F_{av}(Z) = F(a, b, \theta, t, m) \\ R_2 = (1 - a/a_2)^2 + (1 - b/b_2)^2 + \\ \qquad (1 - \theta/\theta_2)^2 + (1 - t/t_2)^2 + (1 - m/m_2)^2 \\ 12 < a_2 < 16, 4 < b_2 < 6, 55 < \theta_2 < 75, \\ \qquad 0.5 < t_2 < 1.0, 1.6 < m_2 < 1.8\end{cases} \tag{6}$$

The multi-objective optimization based on NSGA-II algorithm is further carried out to verify the disciplinary optimization results. In the multi-objective optimization, the peak impact force and specific energy absorption are set as optimization objectives to evaluate the energy absorption characteristic. The mathematical model of multi-objective optimization of the new crash box is expressed as

$$\begin{cases}\text{Minimize } G(Z) = \{1/F_{av}(Z); 1/E_{ESA}(Z)\} \\ \text{s.t.} Z = (a, b, \theta, t, m) \\ F(Z) < 120, 12 \leqslant a \leqslant 16, 4 \leqslant b \leqslant 6, \\ \qquad 55 \leqslant \theta \leqslant 75, 0.5 \leqslant t \leqslant 1, 1.6 \leqslant m \leqslant 1.8\end{cases} \tag{7}$$

Table 2 shows the optimized values of the design variables and objectives under different optimizations. The optimal solution is obtained based on NSGA-II optimization algorithm and CO algorithm. As can be seen from Table 2, compared with NSGA-II algorithm, the quality mass of the new crash box optimized by CO algorithm is decreased by 0.195 kg, and the specific energy absorption is increased by 251.4 kJ/kg.

Table 2 Comparison of optimization results

Design variable	Initial NPR design	NSGA-II algorithm	CO algorithm
a/ mm	12.873	12.477	16
b/ mm	4.449	4.115	6
θ/ (°)	58.67	71.85	55
t/mm	0.776	0.91	0.53
M/kg	1.835	1.711	1.516
E_{SEA}/(J·kg^{-1})	4 211.4	4 462.3	4 713.7

Figs. 6 and 7 show the impact force and energy absorption of the new crash box with different optimization algorithms. As can be seen from Figs. 6 and 7, based on no optimization, multi-objective optimization and multidisciplinary collaborative optimization, the peak collision force value are the maximal, the middle and the minimal respectively, and the specific energy absorption value are the minimal, the middle and the maximal respectively. Thus, the peak force of collision and the specific energy absorption of NPR crash boxes are all improved based on the CO multidisciplinary algorithm.

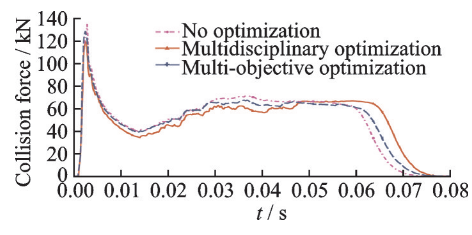

Fig.6 Impact forces of different optimization methods

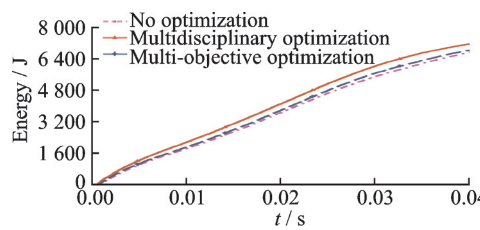

Fig.7 Energy absorption of different optimization methods

Moreover, the NPR structure energy absorption box model is established again for further verification. The collision process of the energy absorption box is simulated at a speed of 16 km/h in LS-DYNA software. Fig.8 shows the deformations of the crash boxes with different optimization methods under the same condition. It can be seen from Fig.8 that the peak value of the collision force without optimization is the largest, the one with NSGA-II optimization is the middle, and it is the smallest with CO algorithm. Therefore, the optimization result under CO algorithm is the best.

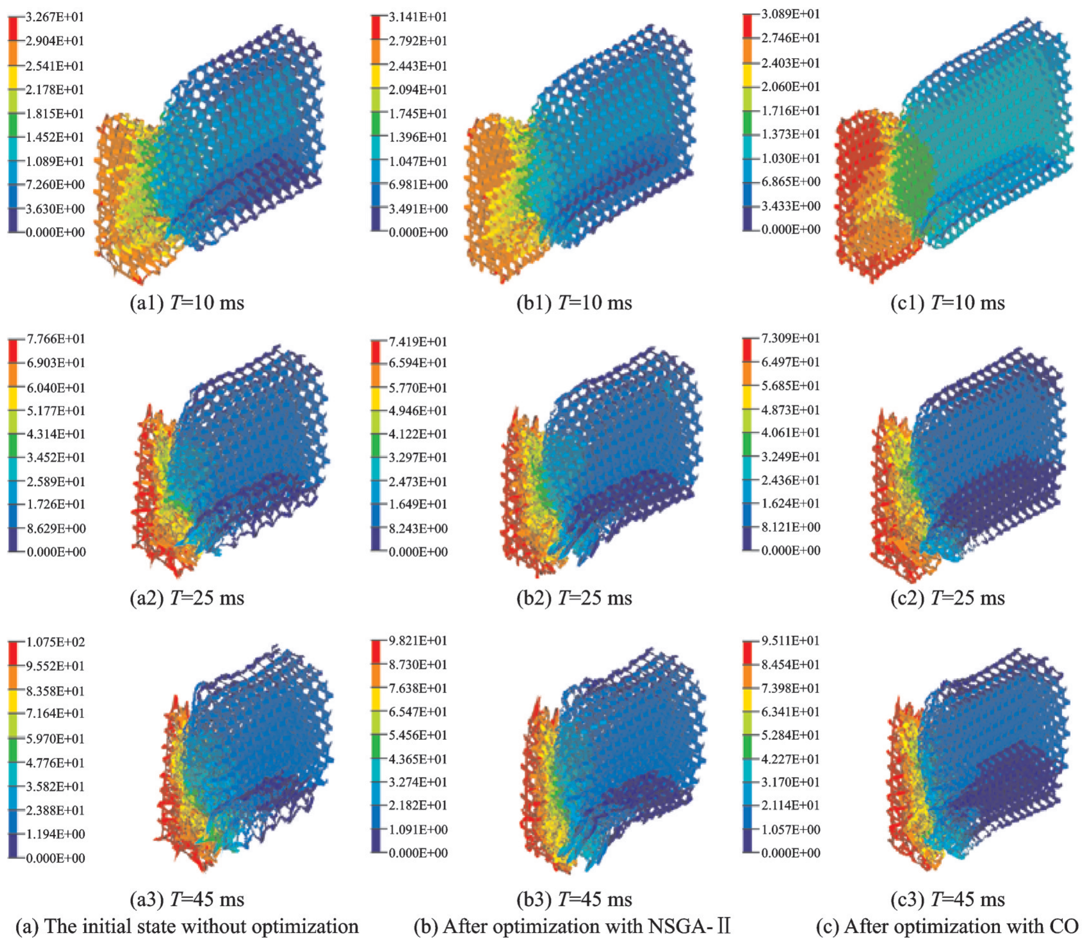

Fig.8 Deformation of three NPR crash boxes

3 Conclusions

The cellular model of the NPR structure is designed, and the mechanical property of NPR structure is analyzed. Then, the optimal Latin hypercube experimental design method is used to select the design variables. Based on it, the RSM of the evaluation indexes are established, and the optimization algorithms of CO and NSGA-II are used to get the optimal solution. The optimization results show that, compared with NSGA-II algorithm, the quality mass of the new crash box optimized by CO algorithm decreases by 0.195 kg, and the specific energy absorption increases by 251.4 kJ/kg. Therefore, the NPR crash box optimized by CO algorithm can improve the crashworthiness and energy absorption performance of the system effectively.

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Author contributions Mr. LU Guangchao contributed to the conceptualization, methodology, investigation, data curation, and formal analysis of the manuscript. Mr. SHU Jiahao contributed to the investigation, software and data curation. Prof. ZHAO Wanzhong contributed to the funding acquisition, visualization, conceptualization, and the supervision. All authors commented on the manuscript draft and approved the submission.

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负泊松比结构吸能盒的多学科优化设计

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摘要: 针对保险杠系统低速碰撞的特点,提出了一种新型的负泊松比结构吸能盒,以提高汽车的耐撞性和能量吸收性能。以峰值碰撞力和平均碰撞力为两个子系统,进行了多学科协同优化设计,并与NSGA-II算法的优化结果进行了比较。仿真结果表明,基于多学科优化方法,新型吸能盒的耐撞性和吸能性能得到了有效提高。

关键词: 吸能盒;多学科优化;负泊松比;能量吸收;低速碰撞