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Finite Element Analysis and Lightweight Design of a Small Cargo Vehicle Frame

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***Abstract* – The finite element analysis and lightweight design of a small cargo vehicle frame structure is carried out. The finite element model of the small cargo vehicle frame is established by using Hypermesh software, and the finite element analysis is carried out based on the bending condition, braking condition, and torsion condition, and the stress distribution cloud diagram of the frame under this condition is obtained. The thickness and width of the crossbeam and longitudinal beam are optimized by the variable density method, and holes are made at the rear end of the longitudinal beam to reduce the dead weight of the frame and achieve the purpose of light weighting.**

***Keywords* – Frame, Variable Density Method, Topology Optimization.**

I. Introduction

As an integral and important part of the vehicle, the frame is responsible for carrying most of the vehicle's load, and its importance is self-evident [1]. Therefore, it is very important to ensure that the frame has sufficient strength and stiffness. Under the condition of ensuring the adequate safety performance of the frame, the lightweight design of the frame can reduce the dead weight of the frame and thus improve the fuel economy and power of the vehicle [2].

At present, researchers are paying more and more attention to the development of automotive light weighting. Gu Antao and Chang Guozhen applied the finite element principle to derive the displacement law matrix equation for thin-walled structures when considering constrained torsion [3]. A multi-objective topology optimization research method was proposed by Wenjie Fan and Zijie Fan. The method avoids the drawback that single-objective topology optimization cannot consider other factors and is suitable for multi-objective topology optimization of continuum structures [4]. Wang Shuting, Liu Xiao et al. established a comprehensive weight sensitivity analysis model for frame stiffness sensitivity, modal frequency sensitivity and static/dynamic structural response for the lightweight design requirements of automotive frames [5]. Yanzhi Nie, Qingfei Jiang et al. derived the dynamic and static stiffness calculation method and target setting basis for the rear subframe suspension bracket [6].

In this paper, a small cargo vehicle frame is taken as an example, based on the CAD model of the frame, material parameters, and finite element analysis of the frame using hypermesh software, the stress distribution clouds of the frame under bending condition, braking condition, torsion condition and turning condition are obtained, and the topology optimization of the frame is carried out based on the variable density method. It provides a reference for the subsequent lightweight design of the frame.

II. Finite Element Modeling of the Frame

The frame of this small cargo vehicle consists of two slotted longitudinal beams, four slotted crossbeams and one connecting plate. The technical parameters of the frame are shown in Table 1. The material used for the frame is B510L, and the mechanical properties of the material are: density is 7850kg/m3; Poisson's ratio is 0.31; modulus of elasticity is 210Gpa; yield strength is 355Mpa. Since this paper only focuses on the lightweight design of the frame itself, the simulation is simplified for the frame steel plate spring, and this paper simplifies a curved plate instead of a plate spring, and gives this curved plate equivalent strength and stiffness to the plate spring. The strength and stiffness of this curved plate is equivalent to that of the plate spring. The applied load on the frame is handled by mass point coupling, and the specific coupling masses are shown in Table 2. The frame is discretized with shell cells in hypermesh software, and the finite element model of the frame is shown in Fig. 1.

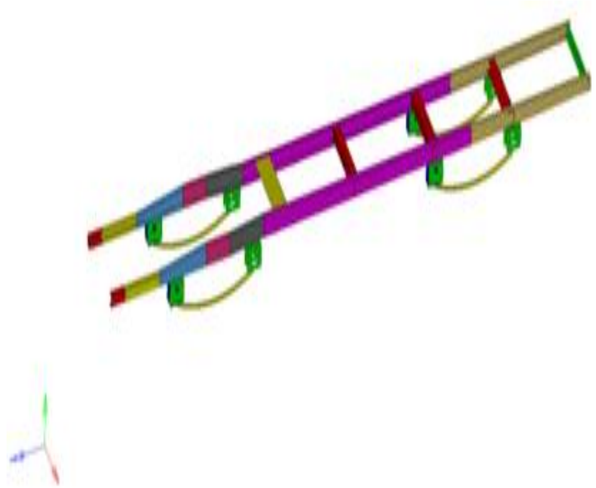

Fig. 1. Finite element model of the frame.

Table 1. Frame related parameters.

Parameter Name	Parameter Value	Parameter Name	Parameter Value
Total length of longitudinal beam/mm	6939	Frame front width/mm	830
Total frame mass (excluding leaf springs)/kg	200.7	Rear width of frame/mm	746

Table 2. Frame Loads.

Parameter Name	Cab and Driver	Containers	Cargoes	Engine, Transmission	Fuel Tank, Spare Tire, Battery
Mass/kg	740	366	1836	540	215

III. Frame Strength

A. *Bending Conditions*

The bending condition refers to the vehicle under full load, uniform speed on a flat road[7], after restraint and load loading of the frame, the stress solved for is shown in Figure 2, the maximum stress to which the frame is subjected is 137.3Mpa appears in the longitudinal beam in the middle of the connecting plate and cross member. The analysis shows that the frame material of B510L, which is subjected to a maximum stress of 355Mpa, and the frame has room for light weight.

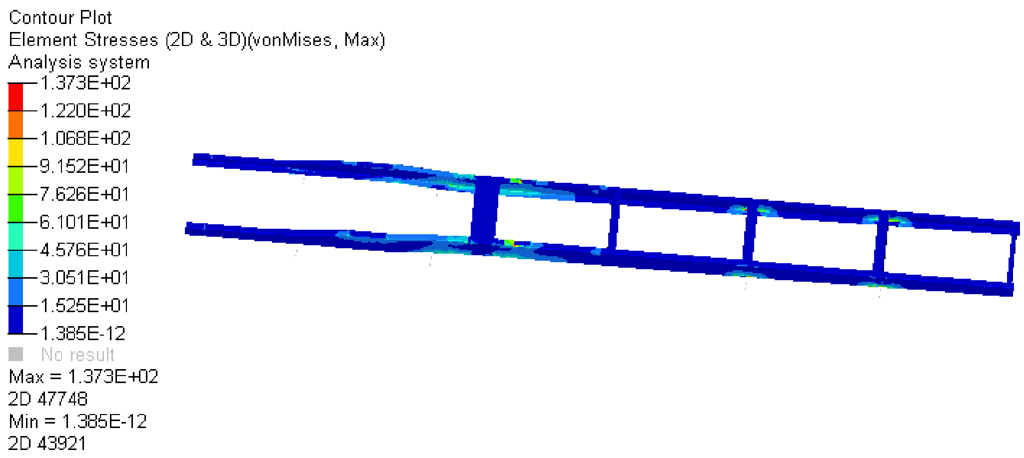

Fig. 2. Frame bending stress cloud.

B. *Braking conditions*

The braking condition refers to the vehicle full load driving process, with a certain acceleration for braking, this paper braking acceleration is taken as 0.7g, after the frame is restrained and loaded, the solved stress is shown in Figure 3, in the braking condition, the frame stress is higher compared to the bending condition frame stress, The maximum stress value occurs at the welding of the longitudinal beam of the frame, its maximum stress is 213.7 Mpa, but in the The maximum stress is 213.7 Mpa, but in the overall part of the frame, the maximum stress is only 47.5 Mpa, there is still a surplus of stress in the frame, and there is room for light weight.

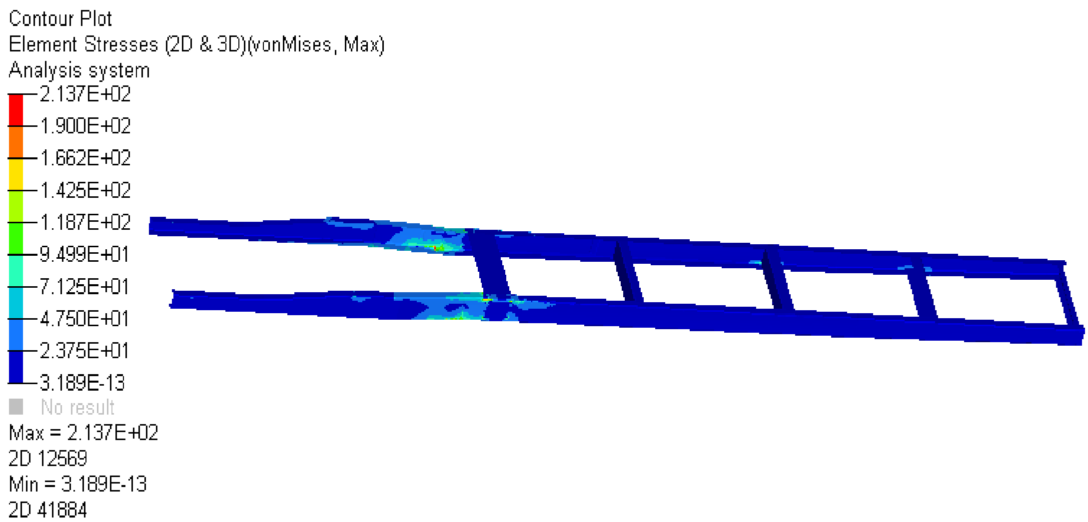

Fig. 3. Frame braking stress cloud.

C. *Torsional Working Conditions*

The torsional condition simulates the force state of the car when one wheel is suspended and the other wheel is raised. After the frame is restrained and loaded, the solved stresses are shown in Fig. 4. The analysis shows that the maximum stress is only 329.3 MPa under the torsional condition, and the maximum stress value appears at the longitudinal beam and the connecting plate, which is a stress concentration phenomenon, which has no effect on the stress of the frame itself.

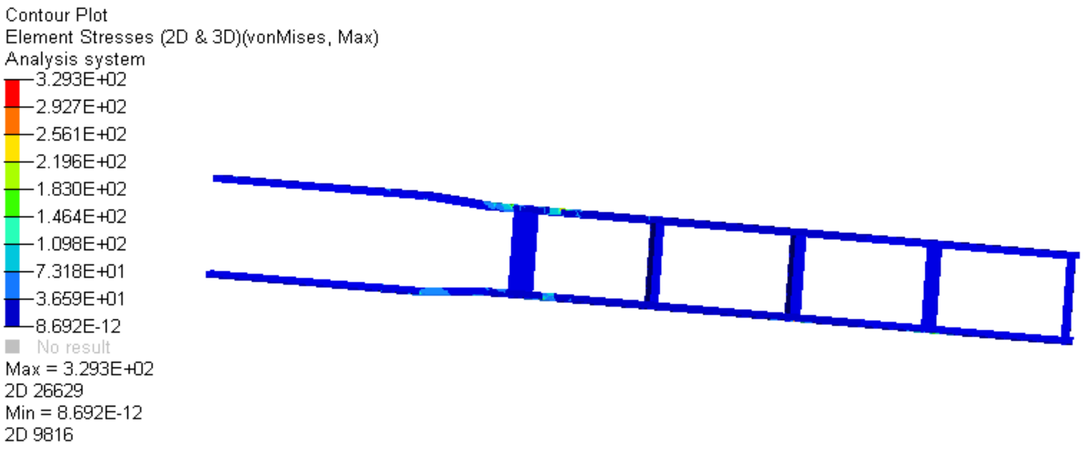

Fig. 4. Torsional stress cloud of the frame.

IV. TOPOLOGY OPTIMIZATION

The flutter optimization requires the establishment of three elements, the optimization variables, the objective function, and the constraints [8]. The light weighting objective of this paper is to optimize the layout of the longitudinal and transverse beams of the frame and reduce the dead weight of the frame, so we set the design variables as the transverse and longitudinal beams of the frame. In this paper, the minimum flexibility is taken as the objective function, the density of the frame unit is taken as the design variable, and the volume fraction is taken as the constraint condition. The mathematical model of frame topology optimization is obtained. As shown in the following formula (1).

$$\begin{cases} find\ \rho = \{\rho_1, \rho_2, \ldots, \rho_e\}^T, e = 1, \ldots, N \\ \min\ C(\rho) = \sum_{k=1}^{m} \Delta k C_k(\rho) = \sum_{k=1}^{m} \Delta k U_k^T K_k(\rho) U_k \\ s.t.\quad \sigma_{\max}(k) \le \sigma_s = 3.45 \times 10^8 pa \\ V(\rho) = \sum_{e=1}^{N} \rho_e v_e \ge V_0 f \\ K_k(\rho) U_k = F_k, k = 1, \ldots, m \\ \rho_{\min} \le \rho_e \le \rho_{\max}, e = 1, \ldots, N \end{cases} \tag{1}$$

Where: ρ denotes the relative density of cells, the design variable; N denotes the number of cells; m denotes the working condition; C(ρ) is the combined strain energy of the frame for multiple working conditions; Δk is the weight factor accounted for by the kth working condition; $C_k(\rho)$ denotes the flexibility of the frame at the kth working condition; U_k denotes the displacement vector matrix; K_k denotes the stiffness matrix; $\sigma_{\max}(k)$ is the maximum stress to which the frame is subjected at the kth working condition; σ_s = 355MPa is the yield strength of the material; V_0 and $V(\rho)$ denote the the displayed volume of the topological base model before and after frame optimization; f denotes the display threshold; F_k denotes the load; $\rho_{\min}$ and $\rho_{\max}$ are the minimum and maximum limits of the design variables, respectively; ρ_e is the relative density of the eighth cell. According to the topology optimization process, the topology optimization is carried out for the bending condition, torsional condition frame, and the calculation results are shown in Fig. 5.

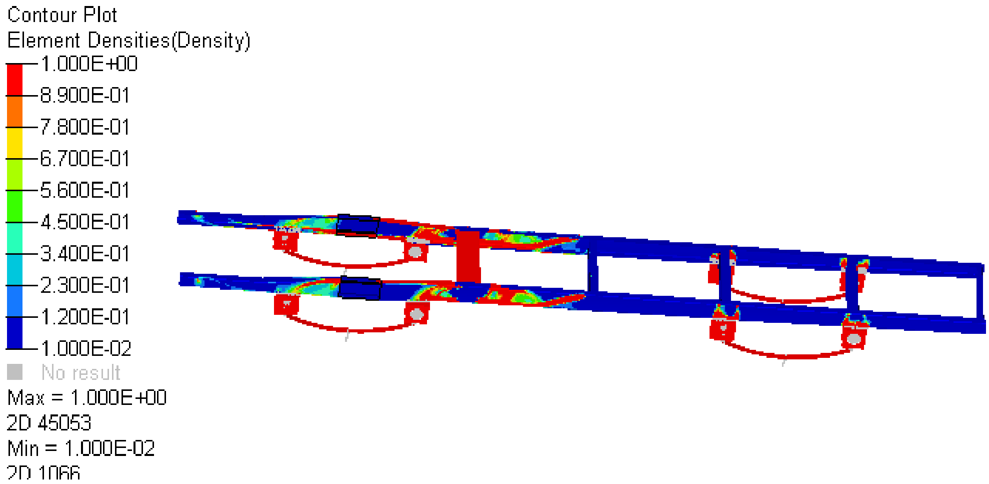

Fig. 5. Topology optimization results.

Through the analysis of the cloud diagram under the bending and torsional conditions, it can be seen that the front end of the frame is subjected to higher stress and can be optimized to a lesser extent, while the rear part of the frame and the cross member have more room for optimization, because the rear part of the frame is subjected to more uniform stress, while the front part of the frame is subjected to higher stress due to the coupling of the cab and the driver passenger and the larger space occupied by the frame. According to the actual requirements of the frame, on the basis of the original frame, the thickness of the two crossbeams is reduced from 6mm to 5mm, and the crossbeam is reduced from 3mm to 2mm, and the stamping opening is carried out at the rear of the longitudinal beam of the frame, as shown in Table 3, and the optimized model is shown in Figure 6.

Table 3. Schematic diagram of the opening.

Location	Opening Shape	Radius/Mm	Quantities
Three-beam vs. four-beam	Round hole	45	4
Three crossbeams vs. two crossbeams	Round hole	45	4
Second crossbeam vs. first crossbeam	Round hole	45	4

Fig. 6. Finite element model after frame optimization.

V. Strength Calibration and Modal Analysis after Optimization

A. *Strength Calibration*

The optimized frame was subjected to stress analysis in bending case, torsion case and braking case, and after applying constraints and loads, the solved stress distribution is shown in Fig. 7, Fig. 8 and Fig. 9.

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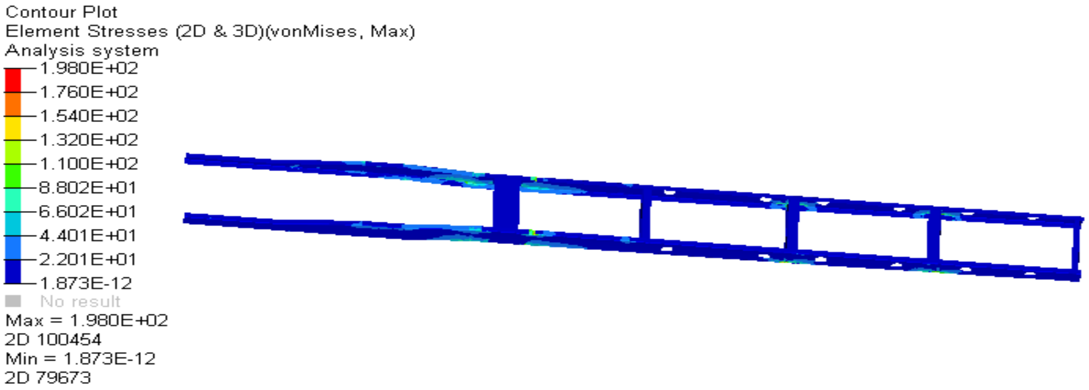

Fig. 7. Stress cloud for bending condition after topology optimization.

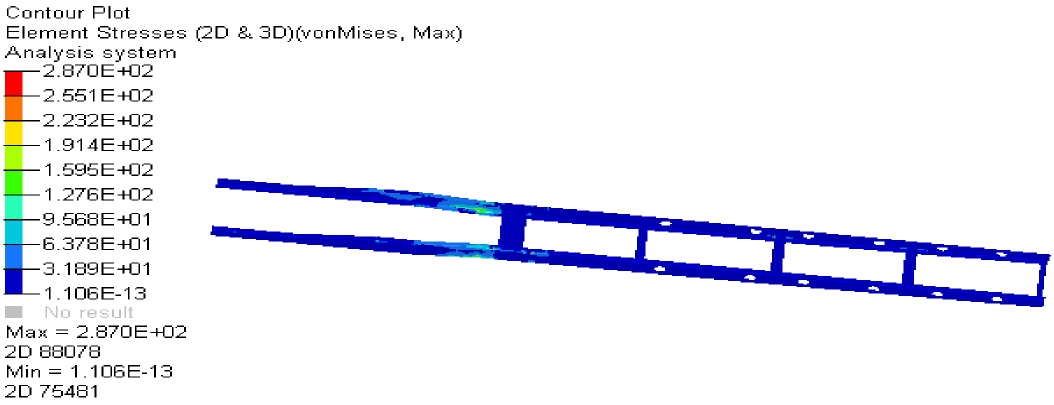

Fig. 8. Stress cloud of braking condition after topology optimization.

Fig. 9. Stress cloud for torsional condition after topology optimization.

The strength check of the improved frame shows that the maximum stress values of the bending condition, braking condition and torsion condition of the improved frame increase to 198Mpa, 287Mpa and 338.2Mpa respectively, but they are less than the yield limit stress of the material and meet the design requirements.

B. *Modal Analysis*

Modes are the inherent vibration characteristics of a structure, and in each mode there is a specific inherent frequency, damping ratio and mode shape [9]. The ultimate goal of the modal analysis is to identify the modal parameters of the system and provide evidence for the analysis of the vibration characteristics of the structural system, the diagnosis and detection of vibration faults, and the optimization of the structure.

In this paper, for the modal analysis of the frame with free boundary, the first tenth order free characteristics and frequency values and vibration patterns are analyzed as shown in Table 4.

Table 4. Modal analysis inherent frequencies and vibration patterns of the frame.

Modal Order	Modal Frequency	Description of Vibration Pattern
1	0.195	rigid body modulus
2	0.003	rigid body modulus
3	0.0009	rigid body modulus
4	0.0005	rigid body modulus
5	0.0002	rigid body modulus
6	0.0004	rigid body modulus
7	10	First order distortion
8	12.1	second order bend
9	12.6	Composite vibration
10	18.1	Composite vibration

The analysis shows that the first sixth order rigid body mode frequency of the model is much less than 1Hz, and the other non-rigid body mode frequencies are all greater than 5Hz, with no local modes below 10Hz to meet the requirements.

VI. Conclusion

In this paper, based on the static analysis of the frame model, the topology optimization of the frame is carried out by comparing the stress distribution cloud diagram of the frame working condition, and the optimization scheme is proposed for the small cargo vehicle, with a weight reduction of 38.7 kg and a lightness of 11.2%. The weight reduction effect is obvious.

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