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Optimization design and crash-worthiness analysis of tank made of aluminum foam sandwich

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Abstract. In order to improve the energy efficiency, environmental protection and safety of the tank, a tank car body was designed as a prototype for the design of foam aluminum sandwich tank body. And then the static performance and Crash-worthiness of the prototype tank body were analyzed by finite element method. The mass, energy abosorption and acceleration of the main parameters of tank strength were analyzed by the MOGA method in Workbench goal-driven optimization, with the results of analysis as constraint conditions. Finally, by confirmed the optimized tank, and the results showed that the static performance and crash-worthiness of foam aluminum sandwich tank body are significantly improved and the mass is reduced, compared with the prototype structure tanker tank. which prove that foam aluminum sandwich tank body in improving the energy efficiency of tankers, environmental protection, especially the effectiveness of security.

1. Introduction

With the improvement of the level of economic development, the demand for oil tank trucks continues to increase. However, with the increase in the number of oil tank trucks, the number of accidents in oil tank trucks has also increased, and these oil tank accidents often occur in tank explosions, which cause heavy losses to the country and people's lives and property [1]. There is no doubt that improving the crashworthiness of oil tank tanks is the most effective measure to curb the collision and explosion of oil tank trucks. At present, the relevant research mainly focuses on the improvement and optimization of the oil tank structure. However, there are few reports on how to use new materials to design and manufacture tankers [1-2]. Aluminum foam has the properties of light weight, high specific stiffness, high specific strength, impact resistance, vibration damping and recovery. It has a wide application prospect in coal mine safety and automobile industry [3-7]. Therefore, the foam aluminum is used as the sandwich material to make the foam aluminum sandwich structure, and the application of it to the oil tank car will reduce the quality of the oil tank car, improve the crashworthiness of the oil tank car, and then improve the environmental protection and safety of the oil tank car. This paper studies the design and optimization of oil tank body with aluminum foam sandwich structure, and simulates its static performance and crashworthiness. It proves the feasibility and superiority of the oil tank with foam aluminum sandwich, and provides a reference for improving the environment and safety of the oil tank trucks.

2. Design of tank body with foam aluminum sandwich structure of tank trucks

2.1. Selection of design prototype

A common hanging oil tank body is taken as a research prototype. Its structure and size are shown in Figure 1. Its cross section is a rectangle with a circular arc of four angles, and there are seven wave guards inside, and there is are two head plates on the sides of the oil tank body. The thickness of steel plate used in the oil tank is 7mm and its material is Q235[8].

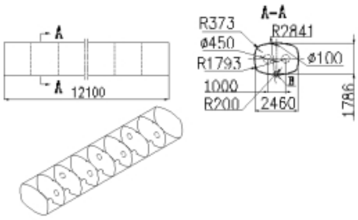


Figure1. Structure of the prototype tank body

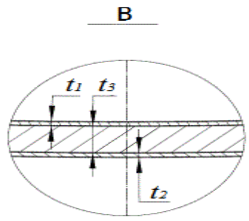


Figure 2. Section of foam aluminum tank

2.2. Preliminary design of oil tank body with foam aluminum sandwich structure

The size of the inner cavity structure of the foam aluminum sandwich structure is the same as that of the prototype, but all the steel plates of the tank body are made of foam aluminum sandwich panels, as showed in Figure 2. The inner and outer panels of the aluminum foam sandwich structure are steel plates whose thickness is t_1 and t_2 respectively. The sandwich material is aluminum foam with a thickness of t_3. The material parameters involved in the two kinds of oil tank body are shown in Table 1.

Table 1. Material parameters

Material	Density/ρ(kg/m^3)	Elasticity modulus/E(MPa)	Poisson's ratio/μ	Yield strength/σ_s(MPa)
Q235	7800	206	0.3	235
foam aluminum	540	12	0.33	24

In order to make the design of aluminum foam sandwich structure tank body meet the rigidity requirements and achieve the lightweight of the tank body. Therefore, the design parameters t_1, t_2 and t_3 should satisfy the inequality equation (1).

$$(\mathrm{EI})_1 \le (\mathrm{EI})_2; M_1 \ge M_2 \tag{1}$$

Where, M_1 and M_2 are the quality of the prototype and aluminum foam sandwich structure tank, respectively. $(EI)_1$ and $(EI)_2$ are the flexural rigidity coefficient of the tank section of the prototype and aluminum foam sandwich structure.

The design parameters are assigned to the flexural rigidity coefficient of the section, and the results are shown in formula (2).

$$E_1(2308.9\times1649.7^3 - 2296.5\times1637^3) \le E_1[(2296.5+2t_1+2t_2+2t_3)(1637+2t_1+2t_2+2t_3)^3 - 2296.5\times1637^3]$$
$$+(E_2 - E_1)[(2296.5+2t_1+2t_3)(1637+2t_1+2t_3)^3 - (2296.5+2t_1)(1637+2t_1)^3] \tag{2}$$

Where, E_1 is the elastic modulus of Q235, 206MPa. E_2 is the elastic modulus of foam aluminum, 12MPa.

The projected area of the tank body contour curve is

$$\Gamma_1^\theta(x)=\int_0^{0.27} x\sin\theta d_{(-0.563+x\cos\theta)}; \Gamma_2^\theta(x)=\int_{0.27}^{1.24}(0.38+x\sin\theta)d_{(0.798+x\cos\theta)}; \Gamma_3^\theta(x)=\int_{1.24}^{\pi/2}(-1.948+x\sin\theta)d_{x\cos\theta} \tag{3}$$

The quality of the prototype tank and the aluminum foam sandwich structure tank is

$$\begin{aligned}&4\rho_1[(L-0.14)(\Gamma_1^{\theta}(R_4)+\Gamma_2^{\theta}(R_5)+\Gamma_3^{\theta}(R_6)-\Gamma_1^{\varphi}(R_1)-\Gamma_2^{\varphi}(R_2)-\Gamma_3^{\varphi}(R_3))]\geq\\&4L(\rho_1-\rho_2)(\Gamma_1^{\gamma}(R_1+t_1)+\Gamma_2^{\gamma}(R_2+t_1)+\Gamma_3^{\gamma}(R_3+t_1)-\Gamma_1^{\mu}(R_1+t_1+t_3)-\Gamma_2^{\mu}(R_2+t_1+t_3)-\\&\Gamma_3^{\mu}(R_3+t_1+t_3))+4L\rho_1(\Gamma_1^{\tau}(R_1+t_1+t_2+t_3)+\Gamma_2^{\tau}(R_2+t_1+t_2+t_3)+\Gamma_3^{\tau}(R_3+t_1+t_2+t_3)-\\&\Gamma_1^{\varphi}(R_1)-\Gamma_2^{\varphi}(R_2)-\Gamma_3^{\varphi}(R_3))+8[(\rho_1t_1+\rho_1t_2+\rho_2t_3)(\Gamma_1^{\theta}(R_4)+\Gamma_2^{\theta}(R_5)+\Gamma_3^{\theta}(R_6))]\end{aligned} \tag{4}$$

Where: ρ_1 is the density of Q235, 7800kg/m^3. ρ_2 is the density of aluminum foam material, 540kg/m^3. L is the total length of the tank body of oil tanker, 12.1m. R_1, R_2 and R_3 are the radius of the cut circle of the inner contour of the prototype tank, 1.793m, 0.373m, 2.841m. R_4, R_5 and R_6 are the external cutting circle radius of the prototype tank, 1.8m, 0.38m, 2.848m. θ, φ, γ, τ are the independent variable in the equation of each contour curve of the tank body, whose value range is [0,π/2].

Considering the thickness of the prototype steel plate is 7mm. The range of t_1 and t_2 of the inner and outer steel plates of the aluminum foam sandwich structure can be taken as 0~3mm. MATLAB software is used to analyze equal stiffness and lightweight constraint inequalities and to fit the surface. Finally, the range of t_1, t_2 is determined to be 1.5~3mm, and the range of t_3 is 25~35mm. In the subsequent multi-objective driven optimization design, the range of parameters obtained will be the optimal interval.

3. Analysis of static characteristics of prototype tank

3.1. Analysis processes

The 3D model of the prototype tank was built by Creo software, and the weld structure was ignored in the modeling process. [9-10]. The model is imported into ANSYS Workbench software to divide the grid into 47547 nodes and 10471 units. The properties of each part of the model are set according to table 1. The constraint conditions are as follows: full constraint is imposed on the bottom of the bottom frame of the tank. The contact type between the head of the tank body and the cylinder body, the cylinder body and the anti wave board, the cylinder body and the wing plate is the binding contact.

The application of the load is as follows: (1) Simulate the weight of the tank body by applying the Standard Earth Gravity; (2) Simulate the weight of the gasoline and the acceleration of the liquid in the tank by applying the Hydrostatic Pressure; (3) The pressure of 540Pa is simulated on the side of the tank; (4) The external pressure calibration force is set to 0.021MPa to counteract the negative pressure produced inside the tank; (5) the longitudinal force of 1125KN is simulated on the front and rear end plates and beams of the tank frame to simulate the longitudinal tension and compression force [11] The load applied is shown in Figure 3.

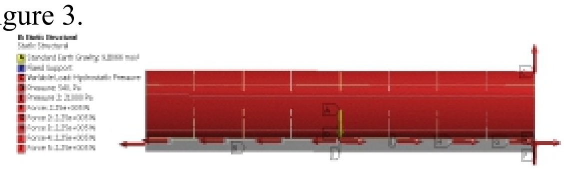
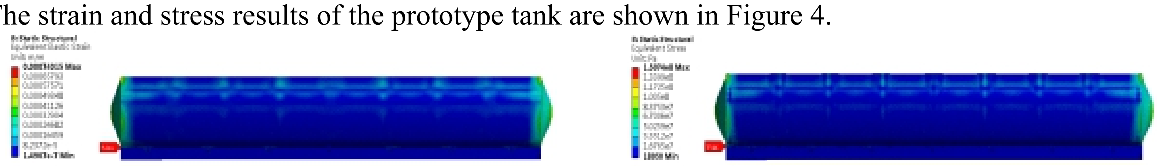


Figure3. Load model

3.2. Results and analysis

The strain and stress results of the prototype tank are shown in Figure 4.



(a) Result of the strain (b) Result of the stress

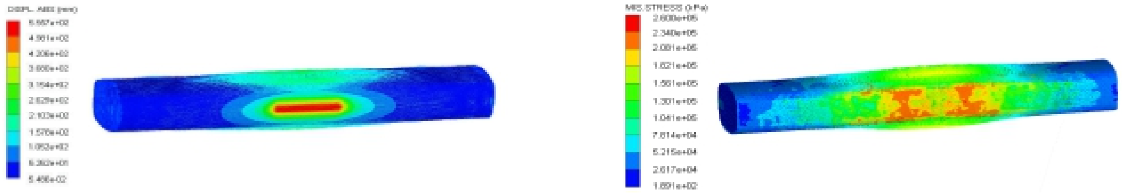
Figure4. Strain and stress of the prototype tank

The simulation analysis shows that the mass of the prototype tank is 36778kg, the maximum strain is 0.74015mm/mm, the maximum stress is 150.74MPa, and the maximum stress is less than the yield strength 235MPa of the Q235 material, which can satisfy the requirement of rigidity and strength of tank body. The results of static characteristics will be used as constraint conditions for the multi-objective drive optimization of foam aluminum sandwich structure tank.

4. Impact resistance analysis of prototype tank

4.1. Introduction to the analysis process
Taking the side collision accident of a pickup truck and an oil tank car as an example, the crashworthiness of the tank body of an oil tanker is studied. The pickup truck is simplified, and the pickup truck model is built using the DM module of ANSYS Workbench. ANSYS Workbench software is used for pre-processing, including setting constraints and solving conditions. Refer to the normal speed of the vehicle on the highway, add a initial 36km/h speed to the collision body.

4.2. Analysis of the impact strain and stress of the tank
The deformation and stress state of 12ms, 24ms, 36ms, 48ms and 60ms during the collision process of prototype tank was studied. Due to the limited space, the results of the termination time are listed, only. This result is also the time of maximum stress and maximum deformation. The result is shown in Figure 5.



(a) Result of deformation (b) Result of stress

Figure 5. Deformation and stress of the prototype tank

4.3. Analysis of impact acceleration response of tank body

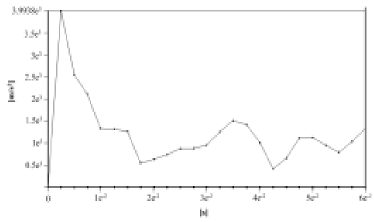


Figure 6. Acceleration curve of prototype tank

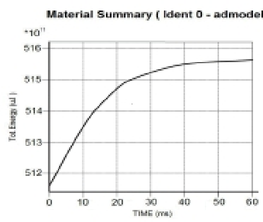


Figure 7. Energy absorption curve of prototype tank

In collision accidents, the maximum acceleration caused by collision is one of the most important factors affecting the safety of the structure of the tank, because it can reflect the size of the impact load of the tank structure. It is an important index to measure the collision performance of tank trucks [12]. The smaller impact acceleration of tank structure, the better the safety of collision. The acceleration curve of the prototype tank during simulation analysis is shown in Figure 6.

4.4. Analysis of maximum energy absorption during tank collision
The energy absorption curve of the prototype tank collision is shown in Figure 7. From the diagram, the maximum absorption energy of the prototype tank is 51566J. The energy absorbed by the simulation is used as the constraint condition for multi-objective driving optimization of aluminum foam sandwich structure.

5. Optimization design of foam aluminum sandwich structure tank

5.1. Optimization steps

The static strength and stiffness of the aluminum foam sandwich structure tank can be satisfied, at the same time, the anti-collision property of the tank can be greatly improved and the quality of the tank can be reduced to the maximum extent. Therefore, it is of great significance to improve the energy savings, environmental protection and safety of the tanker. The thickness of inner and outer plates and the thickness of aluminum foam are used as design variables. Taking the mass $f_1(x)$ of the aluminum foam sandwich structure, the maximum acceleration $f_2(x)$ of the collision and the maximum energy $f_3(x)$ of collision absorption as the objective function. The maximal static stress and maximal static strain of foam aluminum sandwich tank are set as the constraint conditions. Similarly, the maximum stress and maximum deformation of foam aluminum sandwich tank when the collision is less than that of the prototype tank can be regarded as the constraint condition. The MOGA algorithm of Workbench software is used for multi-objective optimization [13]. The optimal mathematical model is as follows:

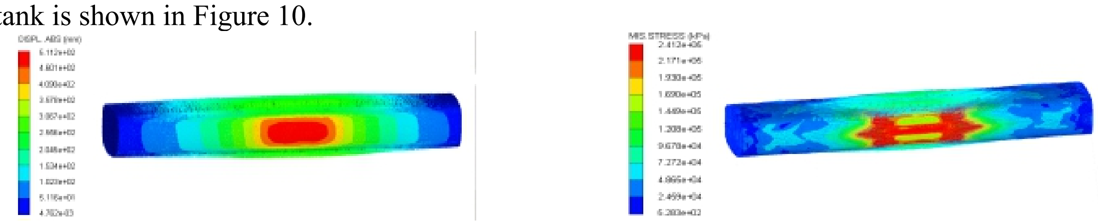
$$\min[f_1(x), f_2(x), f_3(x)]^T$$
$$s.t.\begin{cases} g_1(x) \le 150.74; g_2(x) \le 0.74015; g_3(x) \le 260; g_4(x) \le 555.7 \\ X = [t_1, t_2, t_3]^T \\ 1.5 \le t_i \le 3, i = 1,2; 25 \le t_3 \le 35 \end{cases} \tag{5}$$

The optimized input parameters and constraints are set in the DM module. The thickness of the inner and outer steel plates of the tank is P7 (t1): 1.5~3, P5 (t2): 1.5~3; the thickness of the foam aluminum sandwich is P6 (t3): 25~35. The tank mass P8, maximum acceleration P3 and maximum energy P4 are set as output parameters. The initial values of the design variables P7, P5, and P6 are 3,3,30, respectively. The multi-objective genetic algorithm is used. The initial seed number is 100, the maximum iteration number is 20, the convergence stability ratio is 2, and the maximum allowable Pareto percentage is 70%.

5.2. Results and discussion
After optimization, the design variables are P7=2.3408mm, P6=26.9mm and P5=2.6488mm respectively. According to the standard series size of the existing steel plate, the thickness of the internal and external steel plate of the foam aluminum sandwich structure tank is 2.3mm, 2.5mm, and the thickness of the foam aluminum sandwich is 27mm.

According to the above analysis method, the maximum strain, maximum stress and mass of foam aluminum sandwich structure tank are 0.6135mm/mm, 113.12MPa and 34214kg respectively. Compared with the prototype tank, it decreased by 17.11%, 24.94% and 6.97% respectively. This proves that the aluminum foam sandwich structure can improve the static stiffness and strength and the effectiveness of light weight of the tanker collision.

6. Crashworthiness analysis of foam aluminum sandwich structure tank
In order to verify the improved crashworthiness of aluminum foam sandwich structure tank, the crashworthiness of the tank is analyzed according to the previous method. The maximum deformation and maximum stress which are at the end of the tank crash are shown in Figure 8. The acceleration curve of the foam aluminum sandwich structure is shown in Figure 9. The energy absorption curve of the tank is shown in Figure 10.



(a) Result of deformation (b) Result of stress

Figure 8. Deformation and stress of the foam aluminum sandwich tank

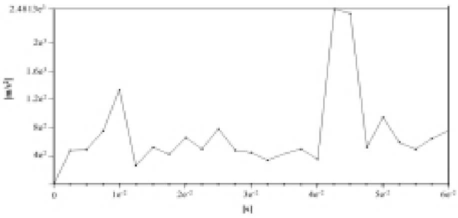


Figure 9. Acceleration curve of the foam aluminum sandwich tank

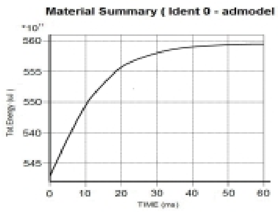


Figure 10. Energy absorption curve of the foam aluminum sandwich tank

In order to further verify the crashworthiness of the tank body of the foam aluminum sandwich structure tank, the performance data of the prototype tank and the aluminum foam sandwich structure can be compared in Table 2. As shown in figure 9~11 and table 2, the acceleration calculation of the foam aluminum sandwich tank is generally lower than that of the prototype tank during the whole collision process, and its peak acceleration is $2.4813\times10^3 m/s^2$, which is 37.87% lower than that of the prototype tank of $3.994\times10^3 m/s^2$. The maximum deformation and maximum stress are decreased to different degrees compared with the prototype tank. The maximum deformation is reduced by 8.00%~22.29%. The maximum stress decreased by 7.23%~15.70%. The maximum energy absorption of the foam aluminum sandwich structure is 55948J, which is 8.50% higher than that of the prototype tank. It is proved that the foam aluminum sandwich structure is effective to improve the collision safety of the tank trucks.

Table 2. Collision performance data of the two kinds of tank

Time	Prototype tank				Foam aluminum sandwich structure tank			
	Acceleration (m/s^2)	Deformation (mm)	Stress (MPa)	Energy absorption (J)	Acceleration (m/s^2)	Deformation (mm)	Stress (MPa)	Energy absorption (J)
12ms	1386	126.6	187.2	51386	643	100.9	157.8	55192
24ms	913	256.1	217.2	51492	715	201.5	185.7	55705
36ms	1480	390.7	239.8	51547	469	303.6	204.3	55783
48ms	1210	471.2	248.9	51575	627	406.8	219.6	55901
60ms	1324	555.7	260.0	51566	782	511.2	241.2	55948

7. Conclusion

(1) The maximum static strain, static stress and mass of the tank with the foam aluminum sandwich structure are 0.6135 mm, 113.12MPa and 34214kg, respectively. The calculation results are reduced by 17.11%, 24.94% and 6.97% respectively compared with the prototype tank. It shows that the aluminum foam sandwich structure can effectively improve the environmental protection and safety of the energy saving and emission reduction of the oil tanker.

(2) The results of crashworthiness simulation analysis show that the maximum deformation and maximum stress of the aluminum foam sandwich tank are 22.29% and 15.70% lower than the prototype, respectively. The maximum acceleration of the aluminum foam sandwich tank is reduced by 37.87%, while its maximum absorption energy is increased by 8.50%. It is further proved that the aluminum foam sandwich structure can effectively improve the safety of the tanker.

Acknowledgments

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