Geotech Geol Eng (2016) 34:703–711
DOI 10.1007/s10706-016-9981-1

ORIGINAL PAPER

Structure Design of New Airtight Blast Door Based on Topology and Shape Optimization Method

Yiping Meng · Bo Li · Yingying Wang

Received: 26 May 2015 / Accepted: 11 January 2016 / Published online: 20 January 2016

Abstract Airtight blast door, as the critical component of underground coal mine, requires high quality. Topology and shape optimization were seldom applied in the structure design of products though they were proposed early. Based on those optimization methods and the experience of structure design, a new kind of airtight blast door was developed in this paper. The main component weight of thus kind of door is 14 % smaller than the current airtight blast door without reducing the blast and impact behavior. The typical optimization method and the example presented in this paper are useful for the original development and optimization design in other products.

Keywords Airtight blast door · Refuge chamber · Rescue capsule · Topology optimization · Shape optimization · Original design and development

1 Introduction

Ensuring the health and safety of all personnel is a prerequisite for production work. Early in the twentieth century, the EU member states issued "equipment and protective systems intended for use in potentially explosive atmospheres directive", which refers to the relevant regulations of the mining equipment and protective systems (Rong et al. 2008; Wang 2000). As the core of coal mine safety protection "six systems" (including monitoring and control system, personnel positioning system, emergency protection system, air pressure self-rescue system, water supply rescue systems, communication and liaison system), underground emergency protection system is the attention focus of the coal industry (State Administration of Work Safety in China 2010). In order to standardize the construction of emergency protection system in coal mines in China, China has made some relevant common standards which should be obeyed by all mining enterprises (State Administration of Work Safety in China 2011). The underground refuge chamber and rescue capsule are important component facilities of the underground mine emergency protection system, and the airtight blast door is its key component.

Topology optimization and shape optimization technique are structural design optimization techniques which are based on the finite element theory. Topology optimization calculation method used in this paper is based on variable density method of

Y. Meng · Y. Wang (✉)
School of Civil Engineering, Hefei University of Technology, Hefei 230009, Anhui, China
e-mail: 745832450@qq.com

B. Li
Power Chassis Part Systems-R&D Center, Ningbo Tuopu Group Co., Ltd., Ningbo 315800, Zhejiang, China

continuum. In other words, the material distribution is taken as the optimization object, and in the given design space, by means of the topology optimization iterations, the element density of the requisite structure is dispersed to 1, while the element density of unwanted structure is dispersed to 0 (Bendsøe 1989). By the topology optimization, the best material distribution scheme can be found in the design space of uniform distribution materials. In shape optimization techniques, the structure shape or the shape of pores are taken as optimization objects, through moving the target element nodes on the surface of the structure, the location of surface element nodes of the best structure are figured out by optimization iterations.

At the present stage, domestic products are mainly based on the reverse development and experienced designs, and the original development, by contrast, lags behind, so the structural design optimization technology is rarely applied in product designs. In recent years, although domestic research institutes have started to focus on the application of optimizing technology, but it is mainly limited to the automotive research field (Zhu et al. 2013; Ji and Ding 2011; Deng et al. 2008; Du et al. 2012). In this paper, the structure optimization is tried to be used in the original design of a type of mine-used airtight blast door for mining of which the quality can be reduced in the premise of state standards requirements.

2 The Design Standard and Performance Analysis of Airtight Blast Door

2.1 The Design Standard

Airtight blast doors of refuge chambers and rescue capsules can keep out a certain intensity of the shock wave and poisonous gas, and viewing windows can be set on them (State Administration of Work Safety in China 2011). "General technical conditions" (Technological Equipment department of State Administration of Coal Mine Safety in China 2011) provides that height of airtight blast doors is not <1.2 m, and the width of them is not <0.6 m, and the explosion shock resistance capability is not <0.3 MPa, and the actuation duration is not <300 ms. Considering the double safety factor, namely, the explosion shock resistance capability is not less than is not <0.6 MPa. Because the airtight blast door belongs to a key part of system, its deformation failure condition is that the maximum deflection of plate is more than 2 % or the deformation is more than a 20 mm, and the failure condition is that the maximum stress of material is more than the yield limit strength, and the seal failure condition is that the relative displacement of required connection requirements is more than 1 mm.

2.2 Performance Analysis

According to the requirements of general technical conditions, in the numerical simulation of escape capsules, the input load should be a kind of plane shock wave produced by high-pressure gas explosion which is 100 m away in the roadway. Because this analysis is only for airtight blast doors, and the explosion shock wave is a typical non-periodic load so that its duration of action is very short, by means of equivalent momentum, the blast shock wave can be transformed into a triangular shock wave which is evenly applied to the surface of airtight blast door (Zhao et al. 2012).

The triangular shock wave loading curve is determined by three parameters: the peak overpressure ΔP, time of pressure increasing T_L and actuation duration of overpressure T_U, as shown in Fig. 1.

The loading rate of shock wave is very fast, and that is to say, generally, the time of pressure increasing TL is a few milliseconds (Luo et al. 2013). According to the general technical requirements, in the numerical simulation of airtight blast door, the peak overpressure ΔP is 0.6 MPa, and the actuation duration of overpressure TU is 300 ms.

Because the structural design method and product design result of the airtight blast door for mining are too detailed as this paper describes, based on the

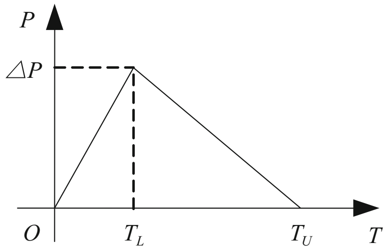

Fig. 1 Schematic diagram of a triangular shock wave load curve

technical secrecy rules of the relevant company, in this paper the time of pressure increasing will be extended to weaken the impact strength acting on the sample airtight blast door (Zeng et al. 2012; Ma et al. 2012), and the complete design idea of airtight blast doors is present in the performance analysis. The time of pressure increasing T_L is 100 ms, and the impact load diagram is shown in Fig. 2.

When the door system is installed, the door frame is welded on the framework of the chamber or capsule, and therefore, without considering the deformation of chamber or capsule, structure, in order to achieve displacement constraint of the door, elements on the welding part are in a full freedom of restraint to limit the displacement of the door.

3 Numerical Simulation of the Explosion Shock Resistance of Existing Airtight Blast Doors

As to the design and development of an airtight blast door of a company, ANSYS/LS-DYNA software is used to simulating its explosion shock resistance capability. The airtight blast door consist of the main explosion resistance structure, sealing structure, insulation structure and the hand wheel transmission mechanism. There are five transverse and two longitudinal strengthening ribs on back of the airtight blast existing door. The structure of the existing door is shown in Fig. 3.

Three dimensional geometry model based on the existing airtight blast door are meshed to form the finite element analysis model. The model used in this paper is dispersed into eight node solid elements, and the average unit size is 10 mm, and the minimum element size is 5 mm. Because of not considering the influence of welding quality against the impact, the welding is realized by nodes overlap in the model. The door hinge is simulated by rotatable elements. The hand wheel transmission mechanism has no effect on the explosion resistance capability, so the simulation of this part is omitted (Gao et al. 2012). The automatic exposure is applied in the overall model. The door body is made of Q345 steel of which the yield strength is 345 MPa. There is a finite element model shown in Fig. 4.

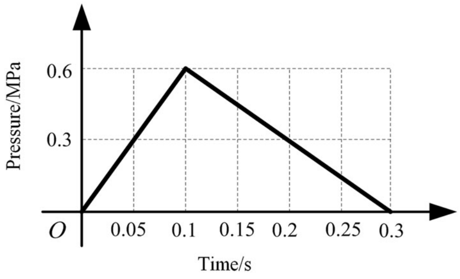

Fig. 2 Schematic diagram of impact load

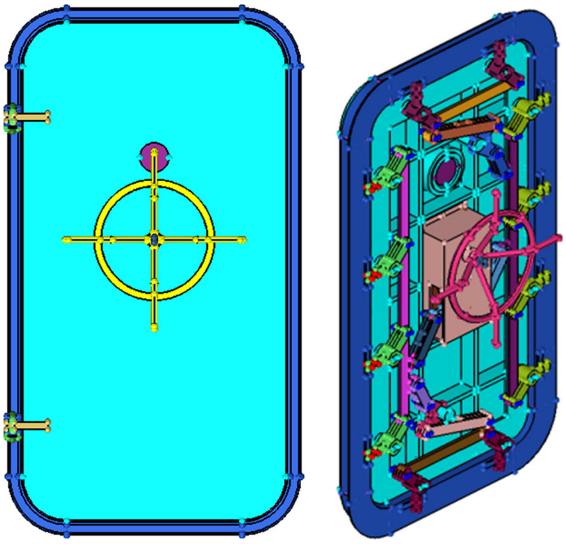

Fig. 3 The existing door structure

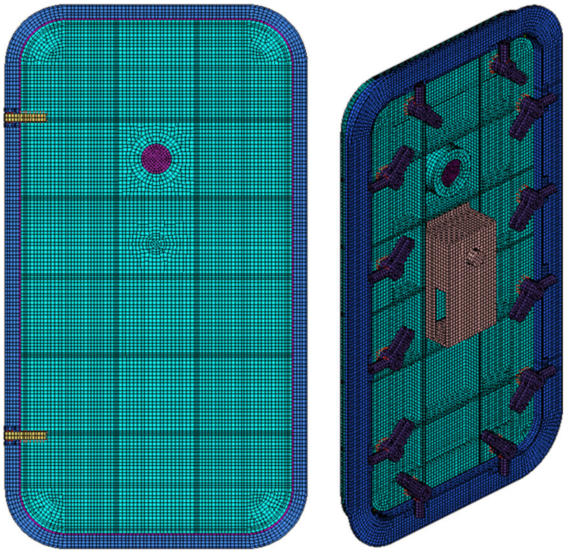

Fig. 4 The existing door body finite element model

According to the numerical simulation and performance analysis, the maximum mises stress is

323.8 MPa which is less than the material yield limit of 345 MPa, and therefore the strength of the door meets the general technical requirements. Under these conditions, the door body is 371 kg in quality.

4 Structural Design by Topology Optimization and Shape Optimization Based on the Existing Airtight Blast Door

As to the existing airtight blast door, Hyperworks/Optistruct software is used in the topology optimization and shape optimization by means of variable density, combining with engineering design experience, a reasonable structure with strengthening ribs and its thickness are designed.

4.1 Topology Optimization

Topology optimization is that, in the design space of existing airtight blast doors, the best arrangement way of strengthening ribs on back of door is searched to reduce the weight of the target door to decrease the cost. The door resists static load when iteratively optimizing. In the iterative calculation, the minimum overall quality is the optimization objective, and that the overall maximum stress is <345 MPa is the limiting condition.

Firstly, the design space for strengthening ribs needs to be determined. The designed structure size of the existing airtight blast door determines the layout space for internal strengthening ribs, and that is to say, the space surrounded by the door panel, the reinforcing plate on the inner edge, sealing plate and the gear box is the topology optimization design space. Without considering the specific structure of the reinforcing plate on the inner edge, the design space for strengthening ribs on back of the door is shown in Fig. 5 (the dark part is the design space for topology optimization, and the light part is the door plate). The element density distribution contour after topological optimizing is shown in Fig. 6 (the density of dark part is 1, and the density of lighter part is 0).

According to the element density distribution contour after topological optimizing in Fig. 6, as to back structure of the door, it only needs four strengthening ribs. Among them, the edge area of the pulled side of the middle two is larger. The longitudinal reinforcing ribs play the role in connection and auxiliary function.

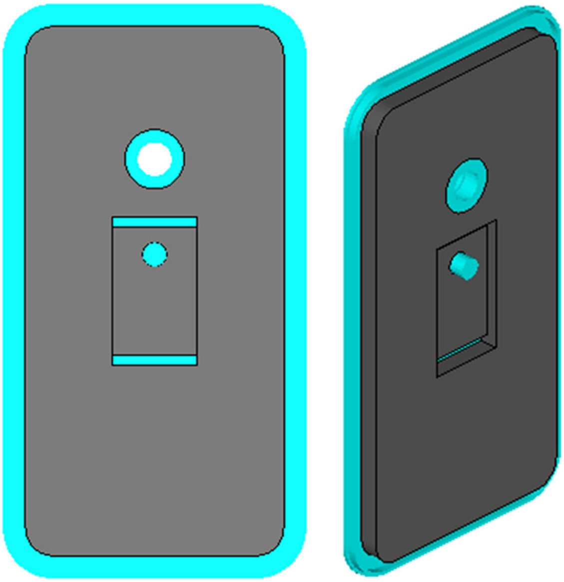

Fig. 5 The design space of strengthening ribs for topology optimization without considering the inner reinforcing plate

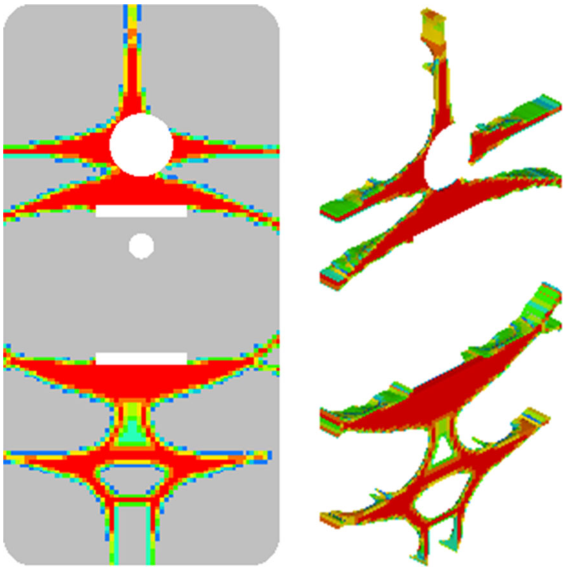

Fig. 6 The element density distribution contour without considering the inner reinforcing plate after topological optimizing

When consideration of the reinforcing plate on the inner edge, the design space for topology optimization changes, and that is to say the structure of reinforcing

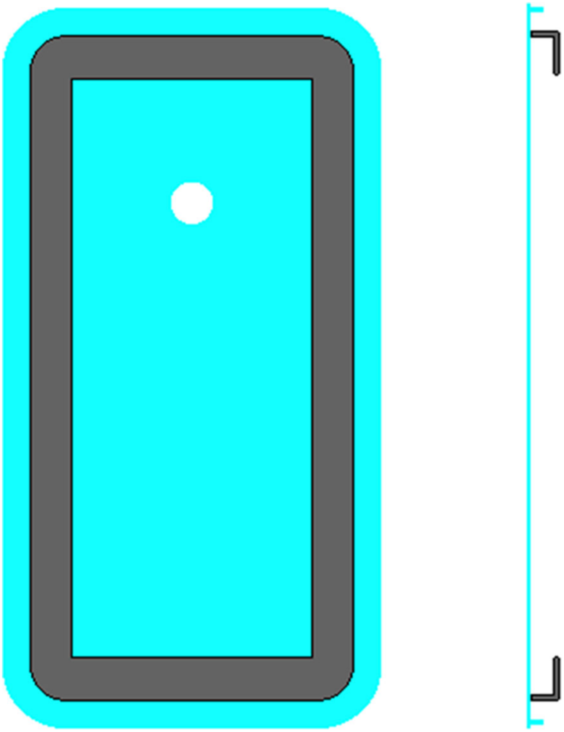

Fig. 7 The reinforcing plate on the inner edge (the picture shown on the *right* is the longitudinal sectional view)

plate on the inner edge has already been identified, and in the topology optimization, the force impact of existing structure should be considered the force. The structure of the reinforcing plate on the inner edge is shown in Fig. 7 (the dark part is the reinforcing plate on the inner edge, and the light is the door plate), it is set to form an internal space for the filling of heat protection material and an installation basis for clamping devices. In consideration of the structure of the reinforcing plate on the inner edge, the design space of strengthening ribs for topology optimization is shown in Fig. 8, and the element density distribution contour after topological optimizing is shown in Fig. 9.

According to the element density distribution contour after topological optimizing in Fig. 9, after the consideration of the structure of the reinforcing plate on the inner edge, the structure of topology optimized strengthening ribs on back of door is different from the former propositional structure. The four transverse strengthening ribs still exist, but the longitudinal ones substantially disappear, and they are replaced by the ribbed plate of the reinforcing plate on the inner edge, and the right angles of the reinforcing plate on the inner edge are changed into filleted corner.

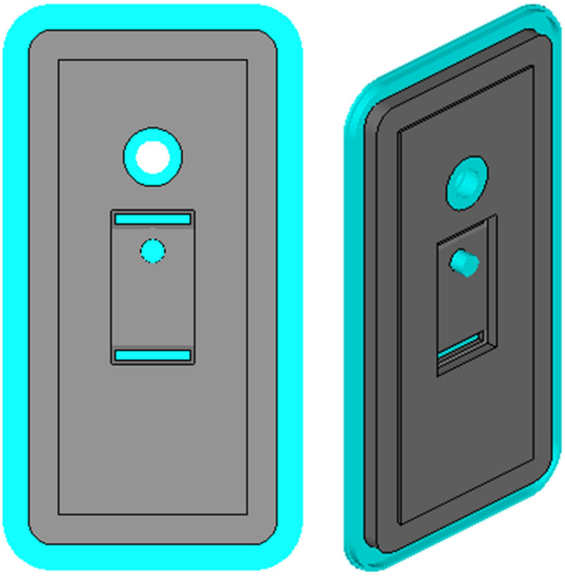

Fig. 8 The design space of strengthening ribs for topology optimization in consideration of the structure of the reinforcing plate on the inner edge

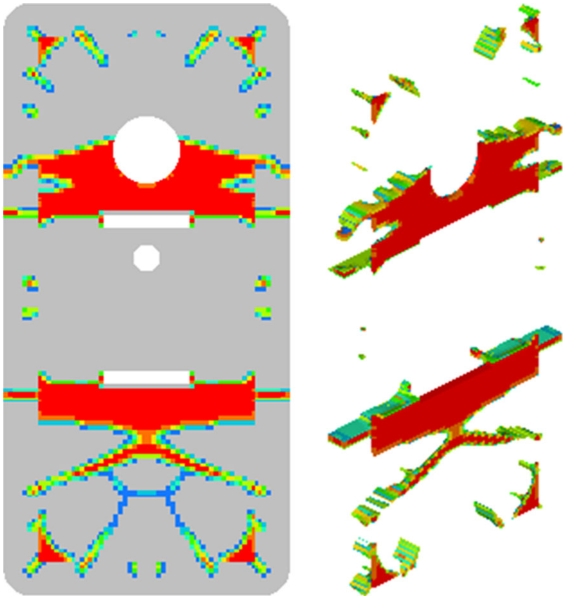

Fig. 9 The element density distribution contour after topological optimizing in consideration of the structure of the reinforcing plate on the inner edge

According to the above two element density distribution results after topological optimizing, the arrangement of four horizontal reinforcing ribs can meet the strength requirement. Because the retained element area the tensile side of strengthening ribs is large, based on engineering design experience, number 1 and number 4 transverse strengthening ribs are made by T section steel, and number 2 and number 3 transverse strengthening ribs are made by L section steel, and the location of strengthening ribs are simply and reasonably arranged. The right angles of the reinforcing plate on the inner edge are changed into rounded ones. Based on the element density distribution after topological optimizing, the ribbed plate of the reinforcing plate on the inner edge is added in the relevant location. The structure of the inner strengthening ribs of the airtight blast door after topology optimization is shown in Fig. 10.

4.2 Shape Optimization

The thickness of the door and the door frame can be optimized. The locations of nodes surface meshes of the finite element model is the optimization variables,

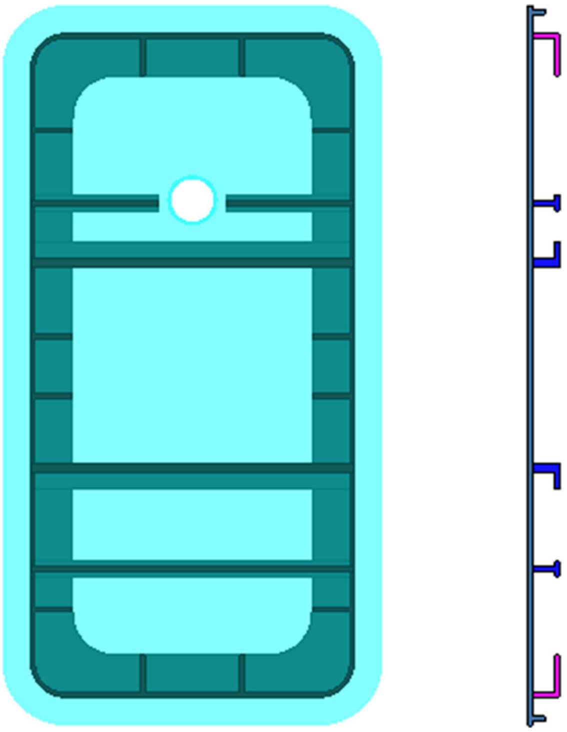

Fig. 10 The strengthening ribs of the door body after the directory design with topology optimization (the picture shown on the *right* is the longitudinal sectional view)

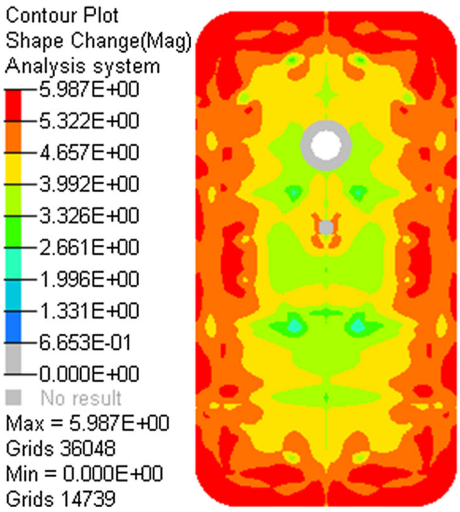

Fig. 11 The deformation picture of the door panel surface after shape optimization

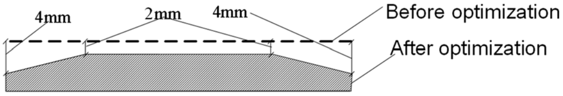

Fig. 12 The schematic diagram of door plate after shape optimization

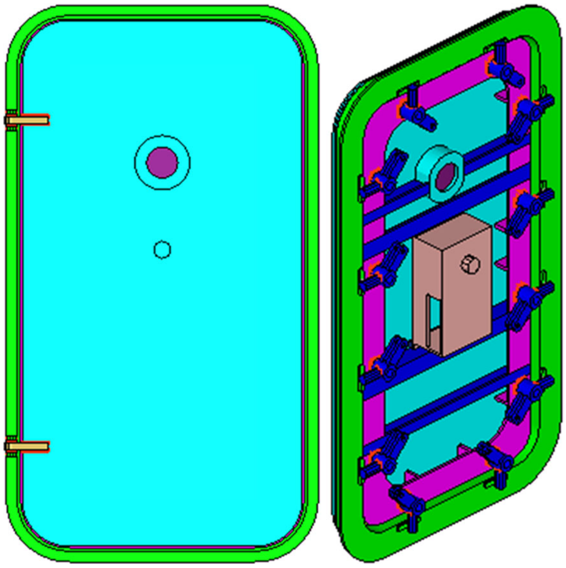

Fig. 13 The new airtight blast door after structure design optimization

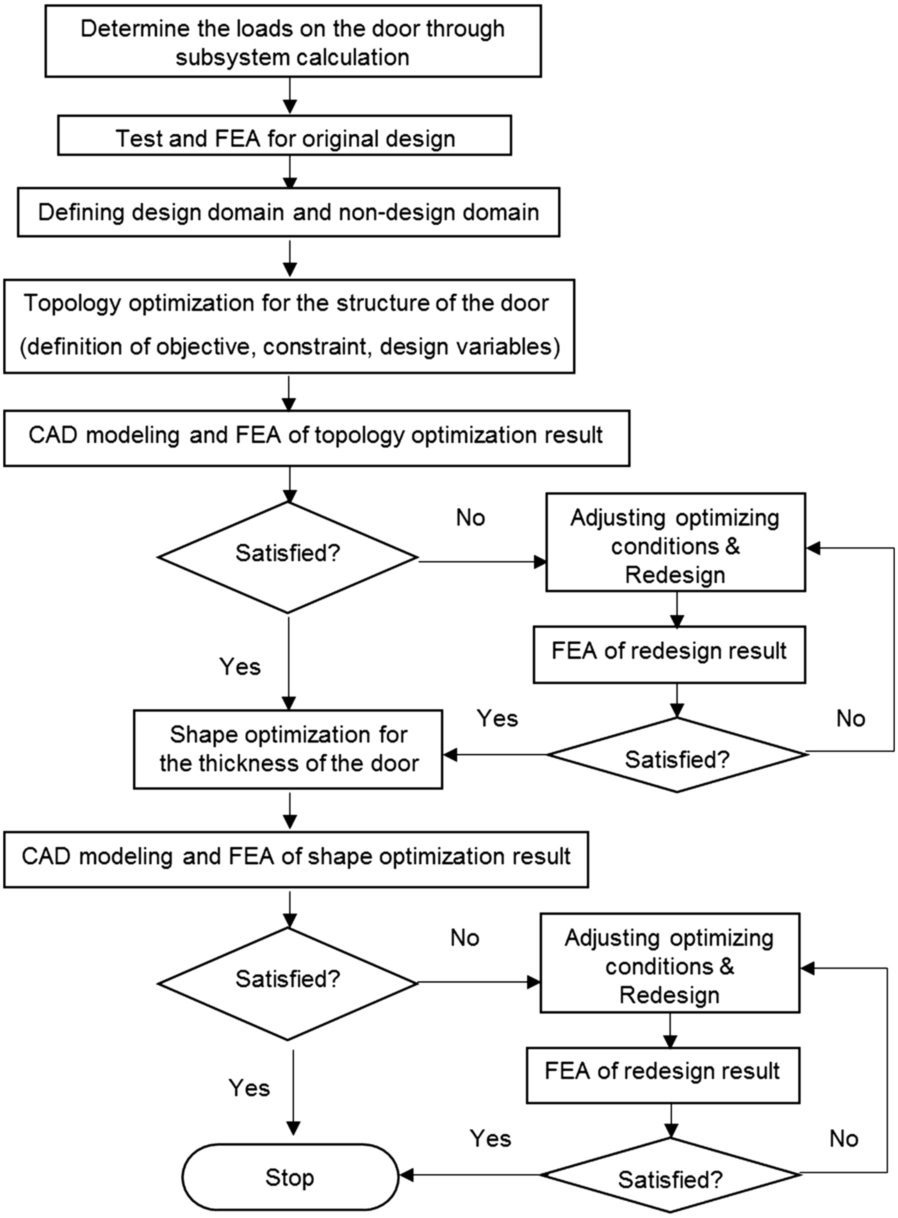

Fig. 14 The flow chart for optimization in this model

and the minimum overall quality is the optimization objective, and that the overall maximum stress is <345 MPa is the limiting condition. On the basis of the results of topology optimization design, the best locations of surface element nodes are searched to decrease the thickness of the door plate and frame and reduce the weight. The deformation picture of the door panel surface after shape optimization is shown in Fig. 11.

According to the deformation picture after shape optimization shown in Fig. 11, the thickness of the all door surface can be reduced by more than 2 mm, and the edge can be reduced by more than 5 mm. In consideration of processing technology, the thinning of the door are near based on the shape optimizing result shown in the deformation image, and that is to say the thickness in the middle rectangular area decreases by 2 mm, and the edge decreases by

4 mm, the thickness between them changes linearly. The section of the after shape optimizing is shown in Fig. 12.

As to the shape optimization of the door frame, the optimization result is completely dependent on the width of lap welding part of the door frame and the escape capsule, and the actual installation width of the door is changeable, so in order to ensure safety in the actual use, the weight of the door frame doesn't decrease.

4.3 Finite Element Analysis of the Door Body After Structure Optimization Design

As to the new airtight blast door (as shown in Fig. 13) after topology and shape optimization design, under the finite element model analysis, the maximum mises stress is 333.5 MPa which is less than the material yield limit of 345 MPa, so the strength of the door meets requirement. The maximum deformation is 5.234 mm which is <2 % of the width of the door (18 mm) and 1.5 % of the length of strengthening ribs (11.5 mm), so the rigidity of the door meets the requirements. As to the relative displacement of connections for sealing, the maximum is 0.39 mm which is <1 mm required in the general technical conditions, so the sealing of the door meets the requirement. Based on these conditions, the door body is 319 kg in quality.

5 Conclusion

1. After topology optimization and shape optimization design, the performance indicators of the airtight blast door meet the general technical requirements, and the structure is safe and reliable.
2. Without weakening the explosion resistance capability, the weight of the new airtight blast door is 14 % less than the existing ones, and the cost decreases significantly. Therefore, the topology optimization and shape optimization techniques can significantly improve the level of original development.
3. In the design of mechanical structures, L steel and T steel can withstand tensile stress well, so as to bending performance of structural strengthening ribs, L steel or T steel is given preference.
4. Adding L steel of ribbed plates can increase the ability of withstanding bending deformation of the cross-section
5. This article provides a typical original development process and classic case in which the optimization design technology conducts the product structure designs, and as shown in Fig. 14, here presents the optimization process which is expected to do a guidance and reference in the original development and structural optimization design of other products.

References

Bendsøe MP (1989) Optimal shape design as a material distribution problem. Struct Optim 1(4):193–202

Gao N, Jin LZ, You F et al (2012) Research and experiment on fireproof anti-explosion air tightness system of refuge haven in underground mine. J China Coal Soc 37(1):132–136

Ji XR, Ding XH (2011) Design optimization of engine hood based on topology and topography optimization. Mach Des Res 27(1):35–38

Lidong M, Haiyan P, Wang Y et al (2012) Numerical simulation of mine rescue capsule to resist the impact of the explosion. J Vib Shock 31(20):172–175

Lizhou W (2000) Equipment and protective systems intended for use in potentially explosive atmospheres directive 94/9/EC. Electr Explos Protect 2:32–37

Mimgyan R, Yong Y, Zhaohong W (2008) Comparison between measurement and test standard system of mine safety production at home and abroad. Coal Sci Technol 36(11):11–13

Na L, Ping H, Xinming Q (2013) The value analysis of the safety of mine explosion rescue capsule structural door antiknock. Chin J High Press Phys 27(006):889–896

State Administration of Work Safety in China. The notice about the Interim Provisions of system in coal mine construction [EB/OL]. (2011-01-27). http://www.chinasafety.gov.cn/newpage/Contents/Channel_5330/2011/0127/122344/content_122344.htm

State Administration of Work Safety in China. Notice on the construction of coal mine safe "six systems" by National Coal Mine Safety Supervision Bureau [EB/OL]. (2010-08-26). http://www.chinasafety.gov.cn/newpage/Contents/Channel_5330/2010/0826/105907/content_105907.htm

Technological Equipment Department of State Administration of Coal Mine Safety in China. Notice of soliciting comments on modifying "Mine portable hardware rescue capsule general technical conditions (draft)" [EB/OL] (2011-09-13). http://www.chinasafety.gov.cn/newpage/Contents/Channel_5330/2011/0914/148421/content_148421.htm

Xianfeng D, Zhijun L, Fengrong B et al (2012) Block design of diesel engine for low vibration level based on topology and shape optimization. J Mech Eng 48(9):117–122

Zeng Y, Bai C, Li J et al (2012) Numerical simulation of rescue cabin under blasting in the tunnel. J China Coal Soc 37(10):1705–1706

Zhao H, Qian X, Li J (2012) Simulation analysis on structure safety of coal mine mobile refuge chamber under explosion load. Saf Sci 50(4):674–678

Zhaoxiang D, Shuna G, Yumei H (2008) Low noise design of car body based on topology optimization analysis. J Vib Shock 27(11):168–172

Zhu J, Lin Y, Chen X et al (2013) Structural topology optimization based design of automotive transmission housing structure. J Jilin Univ (Engineering and Technology Edition) 3:584–589