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Study on the performances of a protective door in coal permanent refuge havens

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ABSTRACT
An effective protective door for an underground refuge haven must have anti-explosion properties, anti-pressure properties, and sealing capabilities. In this study, Wulan Coal Mine's situation and the technical requirements for the protective door in the permanent coal refuge haven were analyzed and a numerical simulation analysis for the anti-explosion performance was performed. The materials, structure, and the sizes of the protective door were confirmed. Further, two experiments on the protection and waterproof abilities of the door were conducted. The results showed that a 15 mm thick 16 manganese steel plate door meets anti-blast and economical requirements. In addition, a manual wedge-shaped lock structure, a single-cast door wall, and a welding steel supporting structure can satisfy the airtight sealing and anti-pressure requirements. In the numerical simulation of the blast effect, it was observed that the maximum displacement was at the centre of the door, and the region of the highest stresses was around the door. The protective door could bear a 1 MPa explosion impact, and it could withstand a 1.86 MPa static pressure load with a deformation of 5.8 mm. Further, the door maintained good sealing performance until the hydraulic pressure exceeded 1.6 MPa with a deformation of 14 mm.
KEYWORDS: Refuge haven; protective door; anti-blast; finite element analysis; performance test

1. INTRODUCTION

Coal is an important basic energy source, and coal reserves account for more than 85% of China's energy resources (Wang and Ji, 2012). At present, Coal mining in China is mainly manual and mechanical. The underground mining environment is complex, therefore, mining safety has become a significant concern. Moreover, owing to the lack of mechanization, mining efficiency is low. In order to ensure the safety of coal miners, the research on refuge havens is of great significance both domestically and globally. The research on refuge havens in developed countries such as the United States, Canada, Australia, South Africa, and others started early, and has achieved fruitful results on underground haven refuge sites, basic protection parameters, and internal oxygen supply for the miners. Further, they have successfully rescued several miners via refuge havens. In August 2010, the State Administration of Coal Mine Safety in China issued on the construction and improvement of coal mine safety hedging "six systems". This document provides a complete set of requirements for the construction of the underground safety hedging systems. Based on the most common types of underground accidents, a refuge haven should include features such as anti-fire, anti-blast, sealing isolation, and oxygen supply (Rick and Graham, 1999). In China, research on refuge havens is in its infancy. At present, China has formed a research system that comprises research institutes, universities, and enterprises. This system has progressed on the basis of the international research achievements, and has gradually developed equipment needed for refuge havens and the related technical requirements (Sun, 2011; Li, 1989; Zhao and Wang, 2007; Michael, 2007; Yang, 2010).

However, studies on protective doors for fire protection, explosion protection, and door sealing are not comprehensive. In this study, the protective door in the Wulan Coal Mine refuge haven is analysed. The stress conditions on the protective door surface are calculated, and the door sealing and blast protection requirements are analyzed to determine the requirements for the door plank material, overall structure, lock structure, supporting structure, and the door size. Further, the capabilities of the anti-blast, anti-stress and waterproofing for the refuge haven-protective door are determined through simulations of the anti-blast, and experiments of anti-pressure, and waterproofing on the door. This study provides evidence and verification for the protective features of the protective door under different conditions. The conclusions made provide important reference to build a complete life protection system and support related technical research.

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2. MATERIALS, STRUCTURES, AND DIMENSIONS

2.1 Protective door materials

Blast-proof materials commonly used for protective doors include Q235 steel, Grade 45 steel, Grade 70 steel, and 16 manganese (16Mn) steel. The mechanical strengths of these materials are listed in Table 1. Among them, Grade 70 steel has the strongest yield strength and can withstand great pressure; however, the product is easy to break, which leads to door deformation. The anti-pressure ability of Grade 45 steel is superior to that of Grade 70 steel, but its corrosion resistance is lower than other materials. The anti-pressure and corrosion resistance abilities of 16Mn steel outperform Q235; however, it is more expensive than other materials. After a comprehensive analysis, for the Wulan Coal Mine refuge haven, it was decided that the 16Mn steel would be used as the material for the protective door plank of the refuge haven, Q235 for the rest materials of the door structure, and the door surface would be sprayed with fireproof and corrosion-resistant paint.

Table 1: Door materials to anti-blast strength comparison.

Material	Yield Strength (MPa)	Modules of Elasticity (GPa)
Q235	235	210
45 steel	355	204
70 steel	420	210
16Mn	350	206

2.2 Protective door shape

The Wulan Coal Mine refuge haven was built in the wall of a tunnel, therefore, the pressure that the door withstood came from the blast wave with a side impact. The door plank could be flat or curved according to the blast shock. The stress analysis is carried out as follows.

Flat door force analysis: the stress process of a flat door is shown in Figure 1. The impact of the explosion is calculated by the following formulas (Yang, 1996; Jian, 2003).

$$R = \sqrt{X^2 + Y^3} = 0.5PS\sqrt{2 - 2\cos 2\alpha} \quad (1)$$

$$D = \frac{0.5PS\sqrt{2 - 2\cos 2\alpha}}{0.5S / \sin\alpha} = P\sin\alpha\sqrt{2 - 2\cos 2\alpha} \quad (2)$$

where, α is the angle between the incident direction and the flat door plank,°; β is the incident angle and reflection angle of the shock wave,°; P is the average stress of the shock wave on the flat door, Pa; S is the surface area of the door, m^2; X, Y are the reaction and the perpendicular reaction to the shock wave, N; R is the total reflection, N; D is the equivalent stress that the door can bear, Pa. According to formulas (1) and (2), when α has an optimal value of π/2, R is P·S. When D is 2P, the reflection and equivalent stress decrease as α increases.

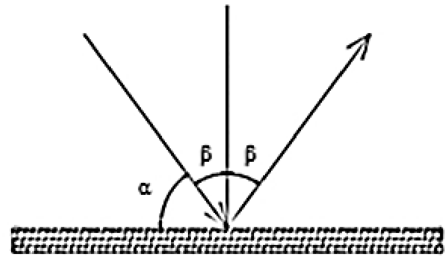

Figure 1: Flat protective door pressure handling

Curved door force analysis: the stress process of a curved door is shown in Figure 2. The impact of the explosion is calculated by the following formulas (Luo et al, 2007; Lin et al, 2008).

$$R = \sqrt{X^2 + Y^2} = \frac{\sqrt{5}}{3}PS \quad (3)$$

$$D = \frac{R}{\pi S} = \frac{\sqrt{5}}{3\pi}P \quad (4)$$

where, α is the angle between the incident direction and the tangential direction of the curved door plank, °; β is the incident angle and reflection angle on the tangential direction of the curved door plank, °; P is the average stress of the shock wave on the tangential direction of the curved door plank, Pa.

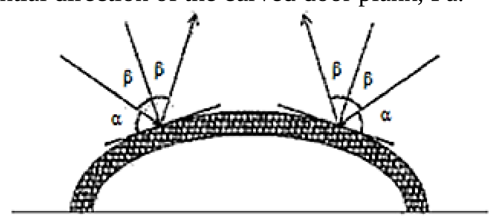

Figure 2: Curved protective door pressure handling.

By comparing the flat door with the curved door in terms of the explosion impact and equivalent stress, it can be seen that both the curved doors and flat panels meet the blast-proof requirements. In particular, the curved door received 25% less impact than the flat door, and the equivalent strength increased to approximately 50%. However, the production of a curved door requires a specialized mold, the processing is more complex, and the cost is relatively high. Therefore, the Wulan Coal Mine eventually selected the flat door for its permanent refuge haven.

2.3 Sealed locking structure

The sealed locking structure of a protective door determines its sealing capability. Common sealing methods include pressure, hydraulic, electric, and mechanical locks. After considering the underground power, air environment, and required door reliability of the Wulan Coal Mine, the mechanical manual lock structure shown in Figure 3 was selected for the refuge haven. The structure adopted the door and four wedge locking devices on the frames. Sealing is carried out by manually rotating the lock against the door frames, with the fire retardant material applied between the flashboards.

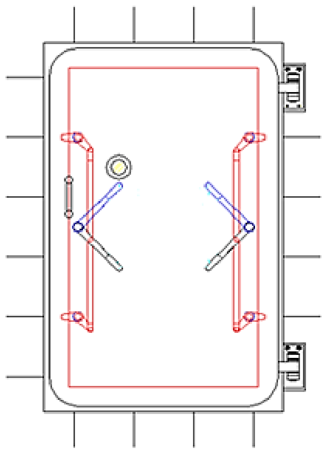

Figure 3: Sealing structure of the protective door.

2.4 Supporting structure

In order to increase the anti-blast ability of the protective door, the overall connection of the door to the wall must be strengthened. To do this, the Wulan Coal Mine permanent refuge haven adopted a welded steel support structure, as shown in Figure 4, for its protective door. The protective door used ferroconcrete, and the wall used concrete casting to create an overall anti-blast airtight seal. When an explosive blast strikes the protective door, the impact would pass through the door supporting structure and be dispersed throughout the wall, which diminishes the effect of the impact (Tian, 1997).

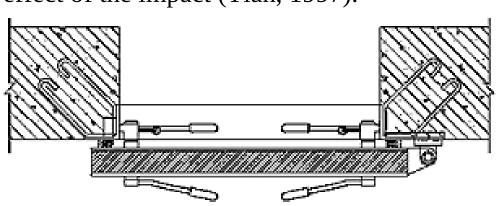

Figure 4: Protective door supporting structure.

2.5 Protective door dimensions

The protective door dimension of the Wulan Coal Mine refuge haven included the door's height, width, and thickness.

(1) Protective door height

The height of the protective door should be decided based on the worker's height and the size of the equipment. It should enhance the door's anti-blast function, yet reduce its exposed area. Through data collection, analysis, and calculations, the average height of the Wulan Coal Mine underground digging, mining, installation, withdrawal, and other operating personnel was determined to be 1730 mm. The largest equipment was the oxygen control device, whose dimensions were 550 × 280 × 1250 mm. Therefore, the protective door height of the Wulan Coal Mine permanent refuge haven was set to 1600 mm.

(2) Protective door width

Through data collection, analysis and calculations, the average shoulder width of the underground workers was determined to be 700 mm. The oxygen purifiers have a maximum width of 600 mm. The width required for equipment transport was also considered, and the width of the protective door was finalized to 950 mm. The overall dimensions of the protective door are as shown in Figure 5.

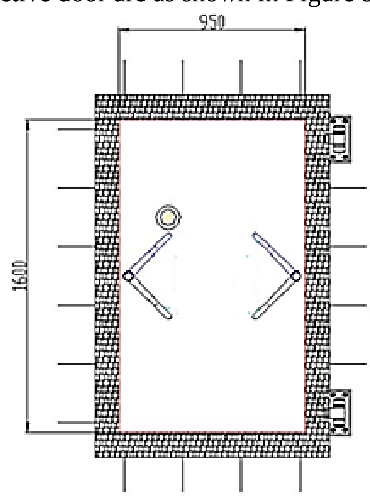

Figure 5: Protective door dimensions.

(3) Protective door thickness

The thickness of the protective door in the Wulan Coal Mine refuge haven was determined based on the incident pressure, reflecting pressure, and static load pressure of the blast (Zhu et al., 2013). The reflecting pressure of the protective door and the static load pressure were determined by the incident pressure. The door thickness (Silvestrini et al, 2008) was calculated using the following formulas.

$$\Delta P_{\lambda} = K\frac{0.196r}{r+1}(M^{2}-1) \qquad (5)$$

$$D = \frac{KK_{d}B}{2\sigma_{D}}\left(2\Delta P_{\lambda} + \frac{6\Delta P_{\lambda}^{2}}{0.7 + P_{\lambda}}\right) \qquad (6)$$

Where, K is the safety factor; r is the air specific heat ratio; m is the ratio of the blast wave speed to the mean speed of sound; K_d is the dynamic coefficient; B is the width of the protective door, σ_D is the pulling stress on the door, and ΔP_λ is the incident pressure. The calculation result showed that the door thickness was 13.2 mm; therefore, the door thickness was set as 15 mm.

3. ANTI-EXPLOSION NUMERICAL SIMULATION ANALYSIS

Based on the door size and material study, 15 mm thick 16Mn steel was selected for the protective door. For the 16Mn steel, the modulus of elasticity is 206 GPa, Poisson's ratio is 0.31, and the yield strength is 350 MPa. A physical model was of a protective door was developed and meshed through finite element numerical simulation analysis. The door load was set to be 1 MPa. The force and displacement on the door were simulated by software ANSYS. Then, the material, thickness, and structure of the protective door in the Wulan Coal Mine refuge haven were assessed to ensure they met the protection requirement (Liao and Ding, 2009; Tan et al., 1997; Lu and Jian, 2003).

4. EXPERIMENT

4.1 Static pressure test

The test door was installed in a doorframe made with ferroconcrete, and it was placed at the ground level with the door suspended in the air. A 10 cm layer of fine sand was placed on the door surface, and it was loaded with high-pressure gasbags to distribute the weight pressure. Next, the airbags were inflated and a static pressure load was placed on the door. At the same time, a CYG712-5 MPa type soil pressure sensor and a BWG2-100 mm displacement transducer were used to measure the door pressure and deformation.

4.2 Airtight and waterproofing test

Two test doors were welded to both ends of a water container, and it was ensured that the welding was sealed and leak proof (as shown in Figure 6). Next, at the bottom of the container, a water valve, pressure gauge, piping, and pressure pump were placed, and a pressure gauge and an air vent were placed on the top to measure internal pressure changes, i.e., the pressure handling capacity of the door. Then, water was added to the sealed container, thus adding pressure into the container. The door deformation and the pressure at the top were measured until the door experienced plastic deformation. Finally, the level of hydraulic pressure the door could take and its deformation conditions were recorded.

Figure 6: Protective door and sealed container for water proofing test.

5. RESULTS AND DISCUSSION

5.1 Numerical simulation analysis

(1) Protective door structure displacement

Figure 7 shows the displacement transformations of the protective door after it was loaded. An analysis of the displacement of the protective door after it bore a 1 MPa load showed that the greatest displacement was elliptical and occurred at the door's centre. The displacement became smaller as it moved from the inside toward the door's borders; the door's centre had larger displacements than the parts around the sealed borders.

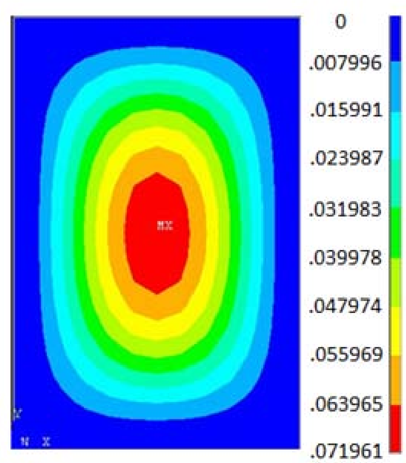

Figure 7: Protect door displacement transformations.

(2) Protective door force

Figure 8 shows the pressure distribution of the protective door model after it was loaded. Based on the door pressure distribution results of numerical simulation, the pressure at the edge was larger than that in other areas after it bore a 1 MPa load. Although the door was depressed after bearing the pressure, it did not become plastically deformed. This shows that if the load added is less than the yield strength that 16Mn steel can handle, then the door does not undergo plastically deformation.

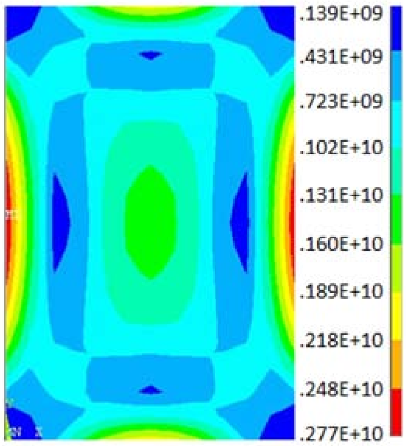

Figure 8: Protective door pressure distributions.

Finite element analysis of the protective door proved that the Wulan Coal Mine's 15 mm thick 16Mn steel flat door could resist a 1 MPa explosion without damage, and it met the 0.3 MPa requirement for anti-fire and anti-blast abilities specified in the current regulations. In order to protect the sealing function from door displacement, a ferroconcrete structure was added and the doors anti-pressure ability was reinforced in order to reduce door deformation.

5.2 Anti-pressure performance of the protective door

Figure 9 shows the hydrostatic load change in the gasbags on the top of the protective door. The pressure and deformation conditions are shown in Table 2. This test proved that the protective door was capable of withstanding a maximum static pressure load of 1.86 MPa, and the corresponding deformation was 5.8 mm.

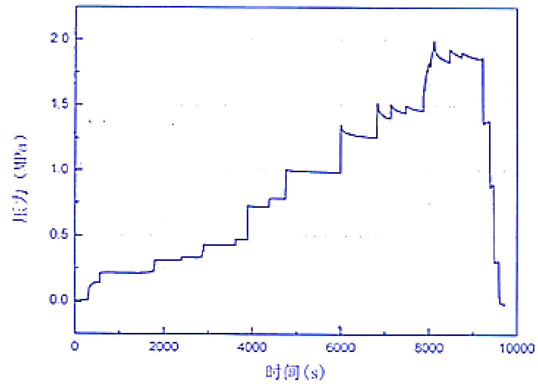

Figure 9: Protective door static pressure load test time - pressure curve.

Table 2: Protective door static pressure load pressure - deformation relationship.

Time(s)	Static Pressure Load (MPa)	Deformation (mm)	Deformation Speed
0-1800	0 -0.35	0-3.0	Steadily increased
1800-6900	0.35-1.50	3.0-4.4	Obvious increase
6900-8100	1.50-1.86	4.4-5.8	Slowly increased
8100-10000	1.86-0	5.8-2.2	Slowly decreased

5.3 Water proof performance of the protective door

Figure 10 shows the relationship between the waterproof feature under pressure and deformation. The hydraulic pressure change for a sealed container filled with water was 0–1.6 MPa. As the hydraulic pressure increased, the door began to deform as follows: "obvious deformation-fundamentally unchanged-slowly increased-maximum deformation" . When the pressure reached 1.6 MPa, the door had a maximum deformation of 14 mm. In the test, there were no leaks or unusual sounds. This test proved that the protective door of the Wulan Coal Mine permanent refuge haven could withstand 1.6 MPa hydraulic pressure and maintain a good seal.

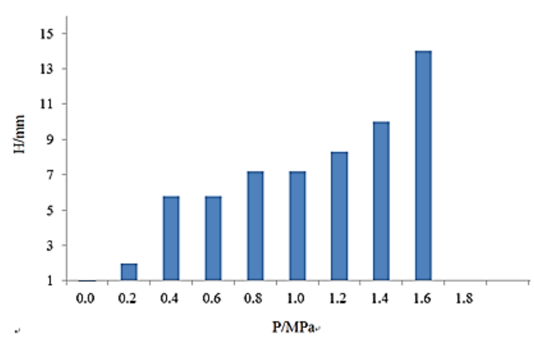

Figure 10: Protective door pressure – deformation.

6. CONCLUSIONS

This study confirmed that the protective door in the permanent refuge haven of Wulan Coal Mine was made with 16Mn steel, with a flat door structure, and used a manual wedge-shaped locking system. The doorframes and walls were supported with ferroconcrete and cast concrete to ensure the ability for anti-blast and airtight sealing. The dimensions of the door were 1600 mm (height), 950 mm (width), and 15 mm (thickness).

Finite element analysis proved that in the permanent refuge haven of Wulan Coal Mine, the door centre had the greatest displacement with the largest pressure at the edges, when it born the blast shock in the tunnel, and it could withstand a 1 MPa explosive impact without plastic deformation. In order to increase the anti-blast protection, the door was reinforced with a ferroconcrete structure.

A static pressure load test confirmed that the door withstood a maximum static pressure load of 1.86 MPa, which corresponded to a deformation of 5.8 mm. The sealed waterproof test confirmed that the largest anti-pressure of the protective door was 1.6 MPa, which corresponded to the deformation of 14 mm with a good seal.

7. ACKNOWLEDGEMENT

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