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STUDIES ON PERFORMANCE OF IMPACT RESISTANT STRUCTURE OF HYDRAULIC SUPPORT IN FULLY MECHANIZED MINING FACE UNDER ROCK BURST[1]

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In order to solve the support problem of a fully mechanized coal face under rock burst and with the goal of safe and efficient coal mining, the present study has envisaged a hexagon periodic arrangement energy absorption structure. Based on the shell theory, the mechanical model of the impact resistant structure and hydraulic support was constructed using the finite element method. The mechanical properties of the hydraulic support under a full impact and a partial load impact of the roof were analysed, and the impact resistant structure was designed to prove the reliability of the structure. The results showed that the anti-impact structure reduced the stress and stress fluctuation of the column and effectively reduced the shape variable of the weak link of the hydraulic support. Furthermore, a delay in the time was observed, when the pressure of the hydraulic cylinder reached the yield strength, and there was a gain in the time for the opening of the large flow safety valve. Especially, under the action of partial load, the column did not bend, and the hydraulic cylinder was in the elastic range. Our results can provide new insights in the support of rock burst working face, which is of great significance concerning safety in the coal mining.

Keyword: rock burst, energy absorbing structure, finite element, mechanical properties

1. Introduction

Rock burst refers to the dynamic phenomenon of sudden and violent destruction of the rock mass around the roadway or working face due to an instantaneous release of elastic deformation energy, and is often accompanied by tossing of the coal and rock mass, loud noise and air waves (Li *et al.*, 2021; Pan *et al.*, 2021a,b; Jiang *et al.*, 2014). The intensity, frequency, degree of the disaster and the associated disaster of coal mine burst in China varies greatly due to different geological conditions at the mining sites (Tian *et al.*, 2021; Pan *et al.*, 2013). In 1949, there were only 2 mines of percussive ground pressure in China, which increased to 7 in the 1950's, 12 in the 1960's, 22 in the 1970's, 32 in 1980's, and more than 50 in the 1990's. Currently, with the expansion of the scope and an increase in mining depth, mining strength, the number of rock burst mines is more than 100 (Yi, 2021; Qi *et al.*, 2019). Although many measures have been taken in the recent years for prevention of the rock burst, the total number of rock burst has not decreased. In the process of coal mining, the leading liquid support mainly bears the pressure from the roof. In most cases, the pressure of the roof is mainly manifested as an impact force, which is transmitted to the hydraulic support column through the roof. As the transmission speed of the impact force is much faster than the response speed of the safety valve in the column, the safety valve fails to unload (Tang *et al.*, 2015; Wang and Song, 1994). The column load instantly and greatly exceeds the safety valve setting working pressure, and the impact energy is released through deformation of the hydraulic support, thus causing structural damage,

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deformation, instability, fracture and cylinder explosion of the hydraulic support, resulting in coal mine accidents.

In view of the harm of rock burst, some scholars introduce an energy absorption structure into the hydraulic support. Wang and Pan (Wang *et al.*, 2021a; Pan *et al.*, 2020a,b) put forward a design principle of an anti-impact support and developed the anti-impact hydraulic support of roadway with an energy absorption function. Liu (2020) designed a straight tube valving type energy absorbing member for hydraulic support, analyzed the influence of geometric parameters on structural deformation resistance, and carried out multi-parameter global optimization of the structure through a genetic algorithm. Han (2017) proposed a round tubular energy absorbing and anti-impact member with a ribbed plate, and studied the influence of structural parameter changes on the energy absorbing effect of the member. Wang *et al.* (2021b) proposed a variable gradient thin-wall energy-absorbing component and analyzed the influence of wall thickness difference on the support reaction force and total energy absorption, thus improving the stability and energy absorption capacity of the structure. Through literature search, it is found that existing researches only focus on energy absorption of the energy absorption structure, but for deformation of the hydraulic cylinder, there is no related research on the influence of the energy absorption structure on the hydraulic cylinder.

The construction of the hydraulic support under the impact load was modelled, and the response of the hydraulic support and weak links were studied. Considering, the working face of percussive ground pressure impingement hydraulic support performance requirements, the present study proposed a high reliability impact energy absorption device. Specifically, the dynamic model of the hydraulic support system with the anti-impact device was constructed, and the impact resistance effect of the anti-impact device was analysed, which can provide new insights in the support of the fully mechanized mining face under rock burst.

2. Dynamic response of hydraulic support under impact load

The occurrence of rock burst is essentially a process of accumulation and sudden release of elastic energy in rock mass around the roadway. According to the instability characteristics, the rock burst can be classified into 3 types viz., material instability type, slip dislocation type and structure instability type. Its vibration waveform is mostly of "umbrella shape" or "mushroom shape", and the action time of the release process is very short, generally lasting for 0.2 s, while the real strong impact load is shorter than 0.1 s. In the process of seismic waves manifested by spread of a negative wave, for analysis of the maximum impact, the effects of extreme conditions were applied to the hydraulic support. The roof of the seismic wave was simplified to the sine wave, and did not consider the negative wave function. Based on an earlier study (Wang *et al.*, 2022) with support resistance monitoring data and load characteristics of a smaller magnitude combined with normal supporting load, the load was determined, as shown in Fig. 1.

2.1. Finite element model of the hydraulic support

Figure 2 shows a simplified finite element model of the ZQ1800/23/43D hydraulic support, which is mainly composed of the roof, column, hydraulic cylinder, base and connectors. Due to the complex structure of the roof and bottom plate, a tetrahedral unit was used to divide the grid size of 10 mm, and a total of 685,632 elements were divided. The column consisted of spherical end faces and grooves, and also adopted tetrahedral elements. The mesh size was 10 mm, and a total of 248,154 elements were divided. The hydraulic cylinder was simplified as a cylinder, and the hexahedral mesh was used to divide the cylinder. The mesh size was 10 mm, and 50772 elements were divided. In the traditional mechanical model of hydraulic support, the structure of the hydraulic column is generally simplified as a spring with large stiffness, which is also true in

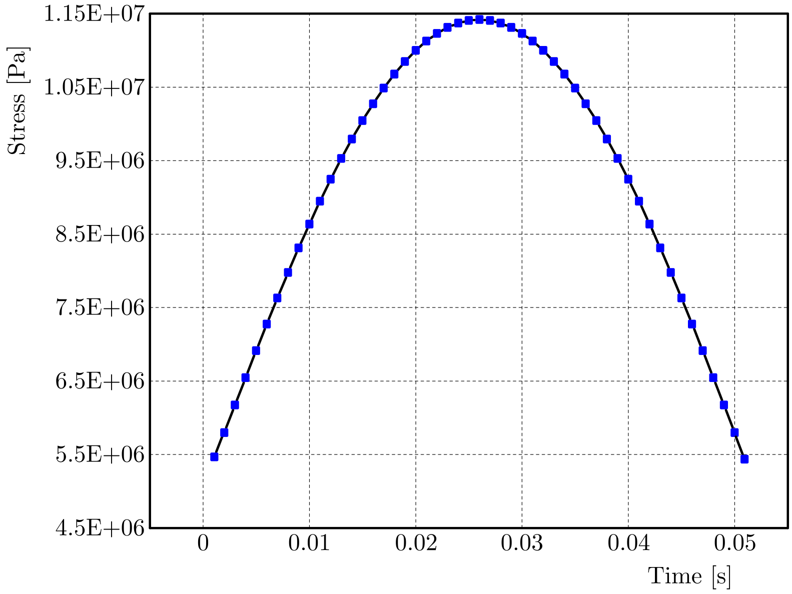

Fig. 1. Characteristics of load

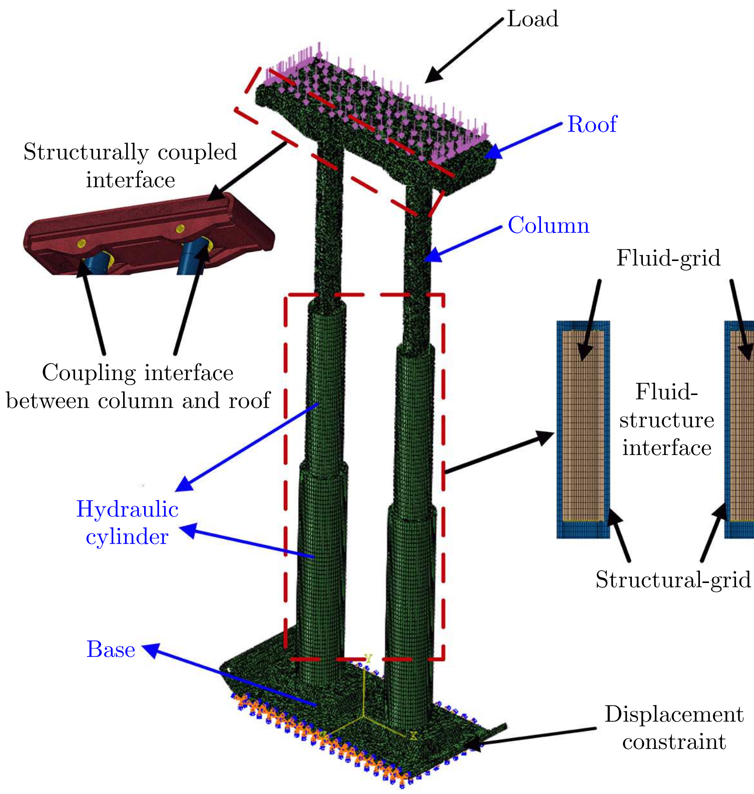

Fig. 2. Finite element model of the hydraulic support

finite element analysis. However, this model does not conform to the actual working conditions, and it is impossible to simulate the expansion and explosion of the hydraulic cylinder caused by pressure. Therefore, the liquid in the cylinder is taken into account, the hydraulic cylinder is divided into 32006 hexahedral cell grids to simulate the liquid (since duration of the rock burst is very short, and the safety valve at the bottom of the hydraulic support does not get opened within such a short time, the flow of the liquid in the cylinder is not involved in the simulation process). In addition, compared with the hydraulic support in the support group of the whole mining area, a single hydraulic support was regarded as one point, so the load acting on the support roof was regarded as a uniform load.

Table 1. Material properties

Structure	Modulus of elasticity	Density	Yield strength	Speed of sound	Poisson's ratio
Hydraulic support	210000 MPa	7850 kg/m^3	445 MPa	–	0.3
Hydraulic oil	–	1000 kg/m^3	–	$2.1 \cdot 10^9$ m/s	–

2.2. Results analysis

Figure 3 presents the hydraulic support stress field distribution at different time points. It can be seen that as the time goes by, the stent force gradually increases, and the initial stress concentration is high at the site of the pillar and roof. With an increase in pressure, the hydraulic support force became higher than the material yield strength, and the hydraulic cylinder is the first to reach the yield limit. During the process, plastic deformation of the hydraulic cylinder occurrs, until damage of the structure.

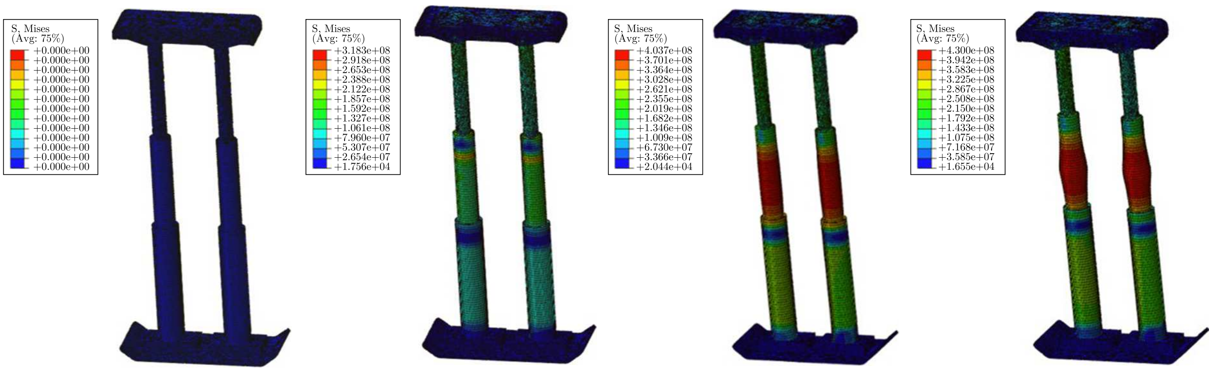

Fig. 3. Cloud diagram of the stress change of the hydraulic support machine

The hydraulic cylinder is the weak link of the system in the impact process. In order to show the changes occurring in the hydraulic cylinder more obviously, the hydraulic cylinder is taken out separately, and the stress change displacement is shown in Fig. 4.

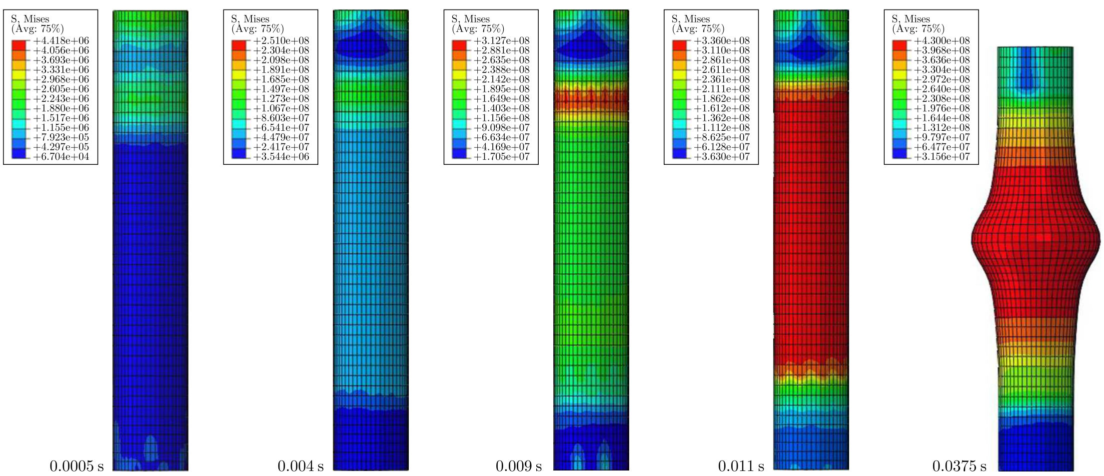

Fig. 4. Cloud diagram of hydraulic cylinder stress variation under the impact load

As shown in Fig. 4, in the initial stage, the stress in the outer wall of the hydraulic cylinder is small, and the displacement change is basically zero. Subsequently, the stress in the hydraulic cylinder gradually increases, but the system is still in the elastic range, and the shape variable is small. After 0.018 s, the outer wall of the hydraulic cylinder exhibits a slight expansion, showing a slow growing trend, and then the expansion trend continues to increase, until finally it gets damaged.

In the whole impact process, the force on the roof of the hydraulic support is uniform, and the stress concentration occurs at the connection between the column and the roof, but due to its high structural strength, there is no serious deformation. However, the thickness of the hydraulic cylinder wall is relatively small. Under the impact, the pressure in the hydraulic cylinder wall increases beyond the yield strength, and plastic deformation occurs until the cylinder explodes.

3. Study on the dynamic response of the energy absorber and hydraulic support under the impact load

3.1. Energy absorption structure

As shown in Fig. 5, an impact resistant structure with a periodic arrangement of hexagonal tubes has been proposed in this study. The structure under the condition of normal support was designed to meet the requirements of the initial supporting force. The impact pressure for a temporary device can quickly damage the absorption part of impact ground pressure energy, at the same time, deteriorate the hydraulic support force. As a result, the impact pressure it provides time for the opening of high pressure and large flow valves.

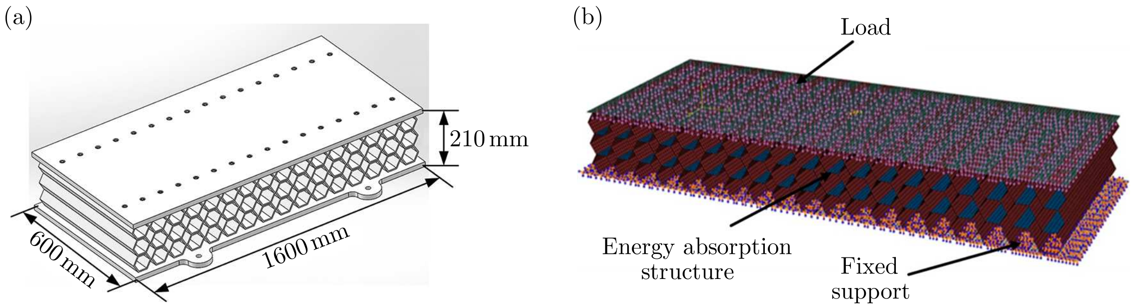

Fig. 5. Impact resistant structural model: (a) 3D-model, (b) FEM model

In Fig. 5, the size of the roof of the energy absorbing structure is the same as that of the hydraulic support. In order to reduce height of the energy absorbing device, there are about 11 hexagonal tubes with a side length of 60 mm in each layer, and large free space is left at both ends. As a result, two layers could not meet the support strength. The height of three layers is over 300 mm, which does not meet the actual installation requirements. Therefore, hexagonal tubes with a side length of 40 mm are selected. The number of each layer is about 18, and the total height of the upper and lower plates is about 210 mm.

In order to ensure that the anti-impact energy absorption device meets the requirements of the initial support force, the static analysis of the structure has been carried out, and the mechanical model of the energy absorption structure was constructed using the finite element method. The length-thickness ratio of the upper and lower plates, hexagonal tubes and other structures of the energy absorption structure were greater than 20. Hence, the shell element was used for simulation, and the grid size was 10 mm, with a total of 65280 elements. The thickness of 2 mm and 3 mm was selected for analysis. The normal support pressure of the unit support roof was about 5.42 MPa.

Figure 6 shows the calculation results of the models with different thickness. When the thickness was 2 mm, the impact resistant structure stiffness was small and could not meet the requirements of the normally working support. When the thickness was 3 mm, the impact resistant structure did not have large deformation, and the overall structure was still within the elastic range, which ensured the normal support of support the unit.

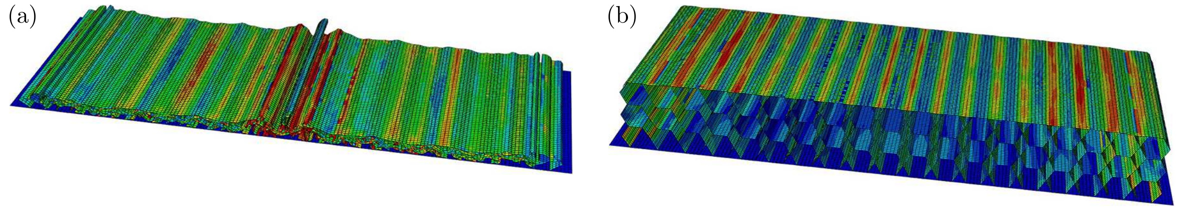

Fig. 6. Calculation results of different thickness models: (a) 2 mm, (b) 3 mm

3.2. Mechanical response of the hydraulic support under an impact load

The hydraulic support model was combined with the energy-absorbing structure constructed in the upper section. The structural coupling interface was constructed on the upper end face of the roof and the ground of the anti-impact structure, as shown in Fig. 7. The load characteristics were the same as above.

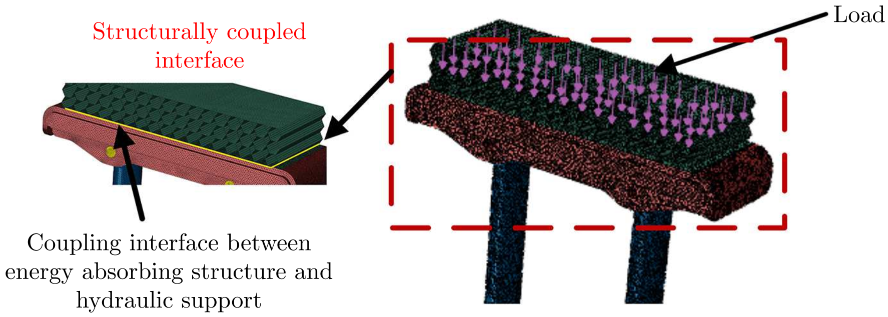

Fig. 7. Impact resistant hydraulic support model

From the calculations, it was found that the hydraulic cylinder was the weak link in the support system under an impact load. Figure 8 describes the stress field distribution of the hydraulic cylinder in the typical state during the impact process. The stress/displacement changes of the joint at the same position of the hydraulic cylinder under the two working conditions were extracted as shown in Fig. 9.

From the calculations, in presence of the impact load, the column (hydraulic cylinder) in the hydraulic support was found to be the weak link in the support system. Therefore, in order to show the effect of energy absorption and the anti-impact device more obviously, the hydraulic cylinder was taken out separately to observe its displacement and stress changes.

In the range of 0-0.011 s, the force on the hydraulic cylinder is small, the maximum stress of the structure is 327.8 MPa, which does not exceed the yield strength of the material, and the structure is in the elastic range. At about 2 ms, the impact load reaches the yield strength of the anti-impact device. After 0.0115 s, the stress in the outer wall of the hydraulic cylinder increases obviously, and deformation of the outer wall of the hydraulic cylinder is less than 1 mm until 0.017 s, and the structure is still in the elastic range. Between 0.018 s-0.0265 s, the growth in expansion of the outer wall of the hydraulic cylinder increases rapidly, and after 0.0265 s, the expansion velocity of the outer wall of the hydraulic cylinder increases.

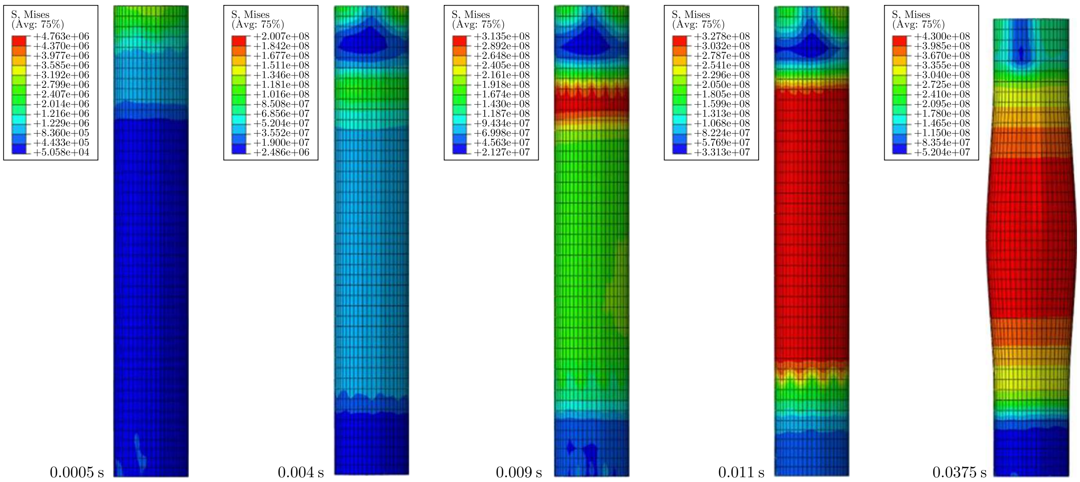

Fig. 8. Cloud diagram of hydraulic cylinder stress variation under the impact load

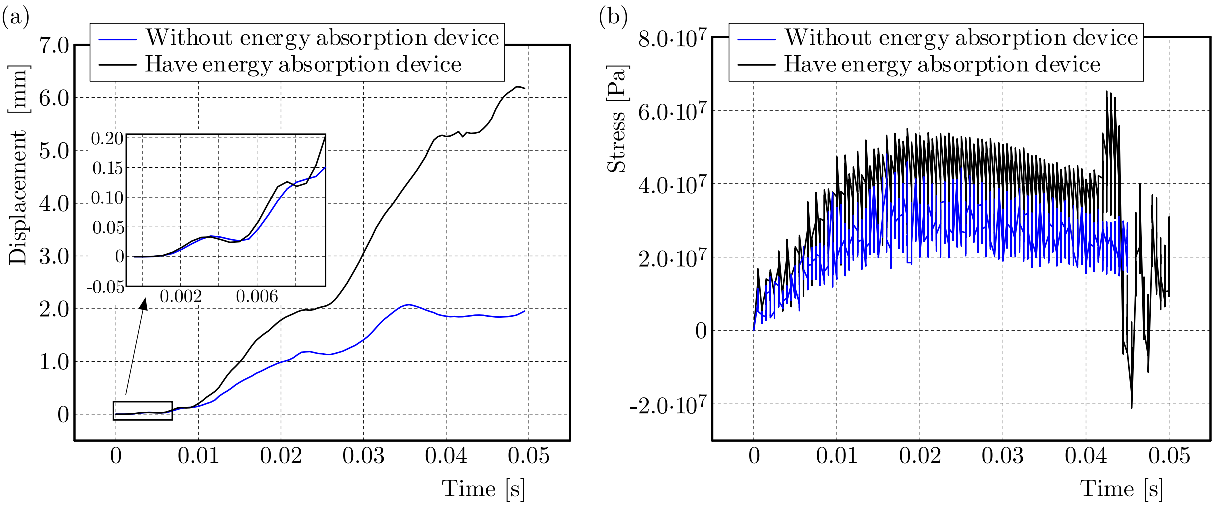

Fig. 9. Displacement/stress change curves of the same supporting system under different working conditions: (a) hydraulic cylinder, (b) position of the column top

It can be seen from Fig. 9 that the displacement presents an overall growth trend. At 0.003 s, a change in the shape of the hydraulic cylinder in the model without the anti-impact structure is about 0.0099 mm, and that in the model with the anti-impact structure is about 0.006 mm. After 0.004 s, the displacement curves of the hydraulic cylinder show obvious differences, and the displacement growth of the model without the anti-impact structure is large. During the whole impact process, the maximum displacement of the hydraulic cylinder in the model without the impact resistance structure is 6 mm, and the maximum displacement of the hydraulic cylinder in the model with the impact resistance structure is 2 mm. Under the action of the impact resistance structure, the deformation of the hydraulic cylinder is reduced by about 66.7%, and the maximum pressure is reduced from the original 50 MPa to a less than 35 MPa (30% reduction). There is a large fluctuation range of pressure between 0.04 s and 0.05 s without the anti-impact device, and the instantaneous pressure peak reaches 60 MPa. In the calculation model with the anti-impact device, the piston force exhibits a stable trend, and there is no fluctuation in a large range.

Although the deformation of the hydraulic cylinder in this calculation model is large, and the force exceeds the yield strength of the material, it is worth to mention that the impact resistant structure effectively reduces the force of the column and deformation of the hydraulic cylinder to a certain extent. In this condition, the damage time of the hydraulic cylinder is extended from 0.014 s to 0.018 s, which is longer under the excitation of seismic wave pulsation. Therefore, it results in a gain of the time required for opening of the safety valve under the short-term high earthquake magnitude.

3.3. Mechanical response of the hydraulic support under a partial impact load

In order to further describe the impact resistance of the energy-absorbing structure, the mechanical response of the hydraulic support was analysed under the impact of a partial load. Considering that the impact surface of the structure was half of the whole, it is worth noting that the other half was still under a static load. Figure 10 describes the stress field of the hydraulic support structure under different working conditions. The displacement curve of the extraction hydraulic cylinder is shown in Fig. 11.

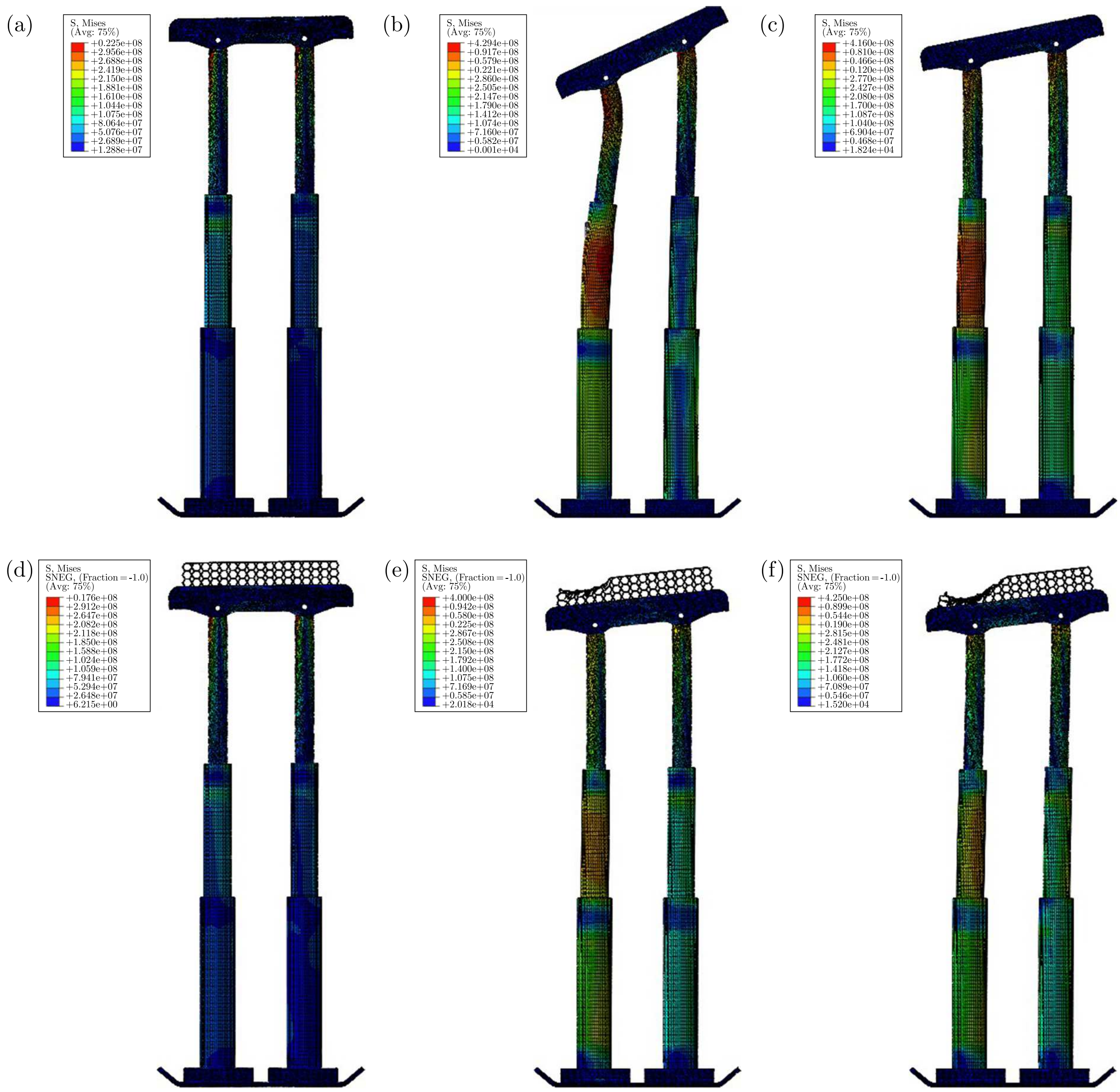

Fig. 10. Mechanical response of the hydraulic support under different impact loads: (a)-(c) without the energy absorption structure, (d)-(f) with the energy absorption structure

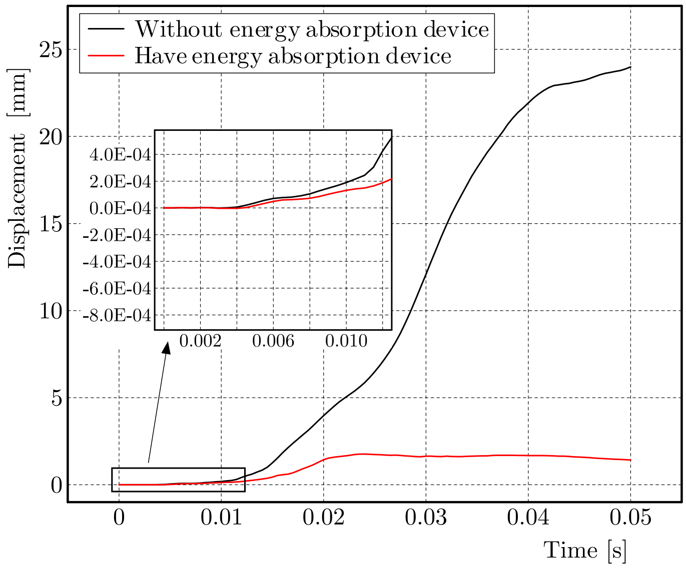

Fig. 11. Displacement curve of the hydraulic cylinder under a partial impact load

Under the action of the anti-impact device, the change in shape of the column and the hydraulic cylinder decreased obviously. The anti-impact device played a positive role, the piston rod and the hydraulic cylinder presented no large deformation, and the column under the unbalanced load side sinked less.

As shown in Fig. 11, the overall variation of displacement presented an increasing trend. At 0.003 s, the displacement curves diverged, and the change in shape at this time was about 0.016 mm. After 0.01 s, there was no impingement device which led to a rapid increase of the hydraulic cylinder deformation in the plastic range. When the impingement device began to work, the hydraulic cylinder deformation declined down to 1.7 mm and the structure was in the elastic range as the load decreased. Hydraulic cylinder deformation gradually recovered.

4. Conclusions

In the present study, considering the problem of the impact pressure of the hydraulic support in a fully mechanized working face support, we proposed a structure of hexagonal tube array impact by employing theory of plates and the shell finite element method to construct the shock structure and a mechanical model of the hydraulic support. Subsequently, mechanical behaviour of the hydraulic support under the action of the impact load was analysed to get the following conclusions:

- Under an impact load, the roof, base and other structures of the hydraulic support did not exhibit a large deformation, while the hydraulic cylinder body presented a large deformation. This is the weakest link of the support system under an impact, and the column was bent under a partial load.
- Due to the effect of the anti-impact device, the time for the hydraulic cylinder to reach the yield strength under the impact load was extended by about 0.0045 s. A change in shape was reduced by about 66.7%, and the force on the top of the column was reduced by about 30%. There was no large fluctuation load, and the displacement of the hydraulic cylinder increased initially, which later decreased under the impact of a partial load. The system as a whole was in the elastic range.

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