Failure Characteristics of W Straps Based on Field Observations and Laboratory Tests

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Abstract

W straps are important surface supporting components. When they cooperate properly with inner supporting components, such as rock bolts and cable bolts, they can enhance the supporting effects and bridging bolting units with integrity. Unfortunately, relevant studies regarding this topic have not been extensively reported. In this study, the failure characteristics of the W strap in the field are discussed and different types of distortion are proposed. Followed by the detailed failure patterns of the strap, a possible mechanism and solution are hypothetically put forward, which are then both numerically and experimentally verified. Afterwards, a loading apparatus capable of examining the mechanical behaviours of the strap is designed, which can similarly recreate the loading environment of the strap to the situation in the engineering field. By virtue of the designed loading device, a series of failure patterns of the bolting system are presented, and the distortion degree of the strap is evaluated using a 3D scanning method. The major findings in this study are as follows: 1) a domed face plate is better than a square domed face plate; 2) the existence of a hole beneath the strap in engineering applications can easily induce failure; and 3) cracked but compacted gravel-like roof strata beneath the strap may not cause damage to the strap-bolt supporting system. These ideas present new understandings in terms of the working conditions of W straps in coal mine roadway supporting systems, and the results can be referred to by practitioners.

Highlights

- In situ failure characteristics of W strap in coal mine support application are discussed based on field observations
- Hypothesis in terms of loading mechanism of different face plates was proposed and thereby numerically calibrated.
- A loading apparatus capable of examining systematic stability of strap-bolt supporting system was designed.
- Failure patterns of strap under different laboratorial settings were 3D scanned and inspected to better understand failure details of strap.

1. Introduction

In the coal mine support area, a complex and unexpected geology can emerge at any time and at any position, which therefore creates numerous difficulties regarding how to appropriately choose the best tool or method to counteract the problems (Chen, 2020; Aydan, 2018; Kang et al., 2018a; Kang et al., 2018b). Looking back at the roadway supporting methods in underground coal mining engineering in the past few decades, there are many examples, such as standing supports, tendon supports and reinforcements, and surface restraint systems (Galvin, 2016; Kang, 2014). For the first type, props, timber chocks, cementitious chocks, steel arches (Lu et al., 2019), sets and pillars are conventional choices; for

the second type, rock bolts, cable bolts, and grouting are most common choices (Smith et al., 2019); and for the third type, trusses and slings, straps, meshes, membranes and liners are common forms.

Among the supporting components proposed above, W straps, when appropriately combined with rock bolts or cable bolts, are one of the most important components that can provide a sufficiently large holding force to roadway roofs in coal mine engineering. They are able to transfer the dynamic load to the yielding tendon, thereby remarkably improving the overall system performance (Simser, 2019; Wei et al., 2018). However, they normally behave weaknesses when applied in high insitu areas (Galvin, 2016).

Relevant studies related to surface support elements, such as mesh and thin spray-on liners (TSL), are very popular (Shan et al., 2019a, 2019b; Nemcik et al., 2009; Spearing et al., 2004; Villaescusa, 2004; Yilmaz, 2011, et al.) Nonetheless, the strength of W straps in a bolting system has received little attention. The difference between wire meshes and W straps is apparent, even though both are pinned on the rock mass by tendons. Fig. 1 shows the supporting effects comparison of a bolt, a mesh+bolt, and a mesh+strap+bolt. The main function of a mesh or lacing is to prevent the brecciated rock mass from dropping between the bolts, so the formation of a cavity can be largely avoided, as seen in section Ⅱ of Fig. 1. For an area with no mesh application, a cavity is likely to form with cracks extending to the deep areas of the roof, as demonstrated in section Ⅲ of Fig. 1. The technological merits of supporting pattern in section Ⅱ of Fig. 1 are apparent when compared with sections Ⅲ and Ⅳ, the load can spread all the way through the entire strap and a potential weak bolting point can be strengthened by virtue of the neighbouring strong bolting point. A supporting configuration such as this is very useful and effective when it is applied to coal mine entries, especially for entries that suffer from abutment pressure from the coal mining face (Frith et al., 2018).

Many *researches* have proven the effectiveness of the mesh from varied perspectives (Feng et al., 2019; Mohamed et al., 2016; Hebblewhite and Galvin, 2017; Heritage, 2019), and a comprehensive supporting scheme that consists of a mesh, strap, face plate, and bolt has been completely acknowledged (Kang et al., 2015; Tan et al., 2017; Zhang et al., 2018; Peng, 2015). Therefore it is widely believed that the rock mass can be stabilized by (Rahimi et al., 2019) using the intrinsic self-stability of the rock mass with assistance from artificial support elements; in most circumstance, support failures in coal mine roadways can be avoided.

Nonetheless, let us examine what occurred in Chinese coal mines while the authors were composing this manuscript (Year 2019). On Nov. 4th, seven people were trapped due to a roof collapse in the Dongrong second coal mine, Heilongjiang Province. Rescue work is in progress and casualties are unknown. On Oct. 31st, a person died due to rib collapse in the Wangjiazhai coal mine, Guizhou Province. On Oct. 26th, seven people died and one person was injured due to a roof collapse in the Shiping First coal mine, Sichuan Province. On Sep. 15th, two people died due to a roof collapse in the Huawei coal mine, Henan Province. On Aug. 2nd, seven people died due to a coal burst in the Tangshan coal mine, Hebei Province. There are too many injuries and deaths to be listed here, and these are only disasters caused by supporting failures; accidents caused by gas outbursts, electromechanical accidents and such are not

included. More can be seen on the website of the National Coal Mine Safety Administration of the People's Republic of China. Therefore, more research still needs to be conducted to understand the properties of the underground rock/coal mass, and more efforts still need to be devoted to coal mine supporting components in order to deepen our understanding of them and their proper selection.

Under such a context, bridging the gap between the mechanical behaviour (failure pattern) of W straps in the laboratory and in the engineering field is meaningful. The content of this study has three sections: first, some typical failure patterns of W straps in the Fujiaao coal mine are presented, and the inducements leading to failure are hypothesized. Second, a laboratory loading apparatus is designed with the purpose of obtaining the loading properties of the simulated bolt-strap supporting system. Third, the testing results are analysed and discussed. The findings in this study will allow coal mine workers to better understand the functions of straps and improve the overall stability of the supporting system.

2. Interpretation Of The Strap Failure In Coal Mine Support

2.1 General distortion of the W strap in an engineering site

Firstly, an engineering site in which the underground support suffered tremendous failure of W strap is exemplified in this section. It is the Fujiaao coal mine in Linfen city, Shanxi Province, China. The supporting pattern consisted of rock bolts, cable bolts, W straps, meshes, and face plates, which is a conventional supporting pattern for coal mine practitioners. Insufficient active support of bolts can easily lead to deformation and dilation of rock mass, the distortion mentioned here can normally be attributed to the generic problems in coal mines (Zhang et al., 2019). In view of the field observation in the Fujiaao coal mine, a common strap distortion type is a fold, which can be classified as either an S-shaped fold, Z-shaped fold, V-shaped fold, inverted V fold, or multiple fold, as listed by the photos in Fig. 2. These distortion types are representative, as all types of strap distortions in coal mines can match their type to a specific form in Fig. 2.

The S-shaped fold near the corner of the roadway is mainly caused by a vertical-shearing drop of the roof along the edge of the rib. Then, an S-shaped fold indicating a small-scale of dropping or a Z-shaped fold indicating a comparatively large-scale of dropping is typical in underground coal mines, see Fig. 2a-b. Sometimes inward movement of the rib also plays a role, which forces the strap to bend.

A V-shaped fold is likely to occur on a roof where non-uniform downward movement of the roof between neighbouring bolting units is prominent, and unequal sagging of the brecciated rock mass forces the strap to bend to form such a distortion, see Fig. 2c. Sometimes in a coal mine roof, an inverted V fold can also be seen. Practitioners tend to attribute this kind of phenomenon to a cavity that exists at the centre, thereby causing the inner border of the cavity to force the strap to deform in the same pattern. However, what is experienced for the engineering case in Fig. 2d is an overlarge bulge of the brecciated rock mass from the left corner, the burst of the rock mass is obstructed by the mesh, then they move together to the bottom right direction of the roadway, forcing the strap to bend. It is noteworthy that the right section of the strap expresses a limited distortion compared with the left section.

The last type is multiple fold, which can be formed under various geological settings, such as a combination of sagging, dropping, or a rightward bulge at the corner, as shown in Fig. 2e. The distortion of a strap can then be very serious, and some rehabilitation process must be executed. In Fig. 2f, a characterized multiple fold distortion is presented, as can be seen where the right rib moves towards the left, which crushes the right section of the strap, adding the extrusion of the cracked rock mass in the roof. Then, the strap completely loses its supporting function and deforms similar to a soft band.

2.2 Breakage pattern of straps in the coal mine field

Detailed breakage patterns of the strap-bolt supporting system are shown in Fig. 3. In summary, the rupture of the rock bolt, decoupling, the rupture of the cable bolt, and shearing through are typical failure patterns, as seen in the figure.

In Fig. 3a, the bolt rupture ends its pinning effects to the strap and the face plate is dropped to the floor before observation. Interestingly, no indentation is found on the surface of the strap due to the compression of the face plate, indicating a small contacting force between the face plate and the strap. Hence, it can be concluded that if the bolt fails before the system reaches a high loading state or a high reinforcing status to the rock mass, then the bolt failure could be caused by an unqualified quality, or water corrosion. A sudden failure of a bolt is likely to occur when corrosion is experienced (Aziz et al., 2014).

Fig. 3b shows a different pattern with what is expressed in Fig. 3a and a conspicuous indentation can be observed, which demonstrates that the bolt failed with the load preserved, prior to the failure. This procedure is typically caused by stress corrosion cracking (SCC) in corrosive environments (Aziz et al., 2014; Wu et al., 2019a, 2019b; Wu et al., 2020). SCC is much faster than environment corrosion in terms of erosion velocity on the steel component.

The strap in Fig. 3c is not in the water dripping environment and the corrosion is not very serious. The bolt was ejected from the borehole, but the exposed bolt could not be pulled out manually in the field observation. Additionally, an indentation of the face plate on the strap surface can be clearly noticed. The indentation proves there is a certain amount of compression between the plate and strap before failure, and the indentation was notched, not because of pretension at the installation stage, but because of a roof subsidence. Note that if the weakest section (thread) along the bolt does not fail, then the failure should be caused by decoupling along the encapsulated section inside the borehole. The diameter of the bolt end is larger than the pure bolt because some remaining resin annulus still bonds tightly with the bolt, so it is easy for the bonded end to become stuck by the broken rock mass during the dropping process. This should be the main reason why the bolt was not able to be pulled out in field, even though it was partially exposed.

In Fig. 3d presents failure of the cable bolt. The cable bolt consists of seven steel strands all together, in which six of them twist around the central one. The failure pattern shows that only three strands were left, and the rupture of the left four strands should be the main reason that leads to the failure of the bolting

system. There is no indentation notch on the surface of the strap, indicating a small compression force between the face plate and a strap prior to failure. Therefore, the bearing capacity of the cable bolt is small. Water corrosion could be one of the reasons when the high erosion state of the strap is considered; another reason could be the shearing failure of cable bolt due to strata movement (Rasekh et al., 2017; Li et al., 2016).

In Fig. 3e and Fig. 3f shearing through of the strap due to sinking of the face plate is observed, with a circular hole left on the strap. The rock bolt and cable bolt both express no signs of rupture or unwinding, which is different to the failure of the bolt or the remaining indentation on the surface of the strap, as shown in previous scenario. Surely such an observation demonstrates the favourable quality of the rock bolt and cable bolt, and the qualified encapsulation section at the bottom of borehole. Possible reasons that account for this type of failure will be discussed in the next section.

2.3 Hypothesis proposition

Regarding the failure pattern in Fig. 3e and Fig. 3f, the hypothesis proposition is hereby discussed. The face plate utilized in the Fujiaao coal mine is dome-shaped with no flat wing around the dome (referred to as a domed face plate in following text and abbreviated as DFP). This type of face plate is different from a traditional square domed face plate, in which the dome is surrounded by a square flat wing (referred to as a square domed face plate and abbreviated as SDFP in the following text).

The stress distribution between the strap and the DFP (SDFP) is presented in Fig. 4. It can be seen that the contact area between the DFP and the strap is circularly distributed and the existence of a high stress concentration is very likely. Whilst for the SDFP, the stress is evenly distributed on the flat area around the dome, so it is unlikely for stress to concentrate at some locations, and the breakage of the strap is avoided to some extent.

Practitioners apply a strap to the roof support with the purpose of enlarging the distribution area of the holding force on the roof. The contact area between the DFP and strap is unfavorable to overall stability of supporting system, and the strap can be tendentiously destroyed. Therefore, the designed supporting force cannot be achieved.

Importantly, the theory proposed above is based on field observations and the hypothesis, and an in-depth analysis is required. Below a simple numerical calibration and laboratorial verification are presented.

2.4 Numerical and laboratorial calibration

A numerical simulation is conducted in this section to examine the correctness of hypothesis proposed above. The simulation model is shown in Fig. 5a. The strap is set as a rigid and non-deformable strap, therefore the stress characteristics of the DFP and SDFP can be compared. For the DFP and SDFP, the elasticity modulus and Poisson's ratio are set as 200 GPa and 0.25, respectively. The density is 7.85

g/cm³, and the eventual load on the top of the nut is 145 kN. Then, stress field of face plate and strap are presented accordingly.

Fig. 5b shows the stress field for the SDFP and DFP from bottom view. It can be seen that the stress on the DFP is larger than that on the SDFP; the stress value around the hole are normally above 300 MPa for the DFP, then the stress decreases as the distance to the hole centre increases, with the minimum value at the outer edge of the DFP at approximately 65 MPa. For the SDFP, the minimum value at the outer edge of the square flat area is below 0.5 MPa, so the stress is more likely to concentrate at areas nearby the hole and the outer edge of the domed part. Some red areas at the outer edge of the domed part have values of approximately 275 MPa, which demonstrates that the outer edge of the domed part in the SDFP is vital for the transferring load.

In Fig. 5c, the stress field on the strap is exhibited. Interestingly, the stress field for the SDFP configuration is not square as imagined in Fig. 4. In contrast, the stress field looks similar to a disk-annulus. The stress field for the DFP also looks similar to a disk-annulus but with a relatively larger diameter, so the stress is fairly uniform with the average value reading at approximately 45 MPa. The largest stress on the strap for the SDFP configuration is 77 MPa, which is increased by 75% compared with the DFP configuration. Under the same loading, the corners of the SDFP are more likely to warp and detach from the strap, then the loading on the SDFP is roughly completely sustained by the outer edge of the domed part. Considering the comparatively smaller diameter of the domed part for the DFP configuration, the stress value on the annulus certainly will be larger than that of the SDFP configuration under identical loading.

In addition to the numerical simulation, laboratory tests on two types of face plates are also conducted, with the results shown in Fig. 6. The face plate is placed on an MTS testing machine, and a cylinder 50 mm in diameter and 50 mm in height is then placed on the top of the hole. The cylinder here is similar to the nut when applied in the *in situ* environment, and it can better transfer the load to the face plate. The loading rate is 5 mm per minute. The relationship of the displacement vs. the load is shown in Fig. 6a. It can be seen that both the stiffness and the peak load for the DFP are much larger than the SDFP. The peak force for the DFP is 369.49 kN, which is 2.78 times the peak load (132.71 kN) of the SDFP. The slope of the linear section can be utilized to characterize the stiffness of the face plate, and the slopes of the DFP and SDFP are 87.94 and 40.05, respectively. A higher stiffness means that the face plate will be more sensitive to a load increase when applied in the engineering field. The end of the test is judged by the first sharp increase along the curve after the peak point, when the bottom of the hole should touch the loading plate of the MTS machine. Based on such a definition, the final displacements for the DFP and SDFP are 15.7 mm and 14.5 mm, respectively, which are quite similar to one another.

In Fig. 6b, the failure pattern of the face plate and the undeformed pattern are presented. Warping of the corners can apparently be noticed for the SDFP; this phenomenon conforms with the numerical results. For the DFP, no warping can be observed through the entire test, and the outer edge is the only bearing place before the centre hole that touches the plate of the MTS machine. Based on this test, the effectiveness of enlarging the supporting area by its flat area for SDFP is undoubtedly unreliable. To a

large extent, the bearing function of the SDFP is mostly dependent on the outer edge of the domed part when the load is too large; the situation can only be improved unless the corners warping can be prevented.

The analysis and conclusion hereinbefore mentioned focused on the bearing capacity of the SDFP and DFP. Based on failure patterns of the strap in Fig. 3e and Fig. 3f and aimed at the hypothesis proposed for the SDFP and DFP, a numerical simulation and laboratory tests were conducted. The results demonstrated that bearing capacity of the DFP is much better than the SDFP and that corners warping is a major weakness of the SDFP. Then, the question is: why does shearing through of the strap in Fig. 3e and Fig. 3f occur and what types of factors trigger this phenomenon? Hence, a more specific investigation is required to fully understand the reacting behaviour between the strap and face plate, which will be discussed in the following sections.

3. Design Of The Loading Equipment For The Strap

3.1 Components interpretation of the loading equipment

Schematic drawings of the loading equipment are presented in Fig. 7, and a structural description is listed in Table 1. On the whole, the loading equipment consists of a pedestal (A), a loading frame (B), a loading box (C), and the strap and affiliated components (D), as shown in Fig. 7a.

The pedestal (A) mainly consists of a baseplate (A1), four support pillars (A2), and a connection plate (A3). On the top of A3, the loading box (C) is pinned on A3 through the connection hole (A31) by a bolts group for the baseplate (A5), as seen in Fig. 7b and Fig. 7e.

The loading frame (B) mainly consists of three sections from the top to the bottom (see Fig. 7c). On the top, three units named the carrier plate in the upper beam (B21), the bottom face of the upper beam (B23), and the vertical plates in the upper beam (B24) form the upper beam. In the middle, two support pillars (B11) are arranged to transfer the load to the bottom section. In the bottom, the lower beam consists of the top face in the lower beam (B18), the vertical plates in the lower beam (B13), and the baseplate in the lower beam (B14). Among these units, the carrier plate in the upper beam (B21) sustains the load sourced from the MTS machine, and then the load is transferred to the testing equipment by the support pillars (B11). The holes (B1a, B2a) arranged at the centre point of the upper beam and the lower beam are set for bolt insertion and bolting during the test process (Fig. 7d and Fig. 7e). There are two nuts to lock the two ends of bolt with one set on the top of the face plate and another one set beneath the baseplate in the lower beam (B14), thereby the bolt can be tensioned, and the system can be loaded.

The drawing for the loading box is shown in Fig. 7f. It is a container that can be filled with different kinds of rock masses. On the top of the rock mass, a tested strap is attached with an assembled face plate and the bolt can be installed with it. It mainly consists of two end plates (C1), two side plates (C2), and one bottom plate (C3). Many types of holes are machined on these plates, and a relative description will be clearer if Fig. 7g is simultaneously considered. The waist-type holes (C1a) on the end plates (C1) are set

for resisting the potential horizontal movement of the strap (D1), and the waist-type holes (C3c) on the bottom plate (C3) are set for resisting the potential vertical warping of the strap (D1). The aforementioned resistance on the strap (D1) is assisted by an assembled pressing plate (Fig. 7h) and pulling plate (Fig. 7i). To be more specific, the tensioned screws (D71) are screwed into the thread holes (D6a) through the waist-type holes (C1a), and the stop screws (D81) are inserted into the plain round holes (D6b) and then into the waist-type holes (C3c). The pressing plate (D5) and the pulling plate (D6) sandwich the strap and they are bolted by locking bolts (D9) through plain round holes (D51), processed end holes (D1b), and thread holes (D6c). In the bilateral the loading box (C), two anchor ears (C4) are assembled, which are able to limit the vibration of the loading frame (B) during the testing process.

Table 1 Structural descriptions of the loading equipment

Label	Description	Label	Description	Label	Description
A	pedestal	A1	baseplate	A31	connection hole
		A2	support pillar in pedestal	A4	corner plate
		A3	connection plate	A5	bolts group for baseplate
B	loading frame	B11	support pillar in loading frame	B1a	through hole in lower beam
		B12	corner plate	B21	carrier plate in upper beam
		B13	vertical plates in lower beam	B22	corner plate
		B14	baseplate in lower beam	B23	bottom face of upper beam
		B15	upper base plate for lower beam	B24	vertical plates in upper beam
		B16	flange plate	B2a	through hole in upper beam
		B17	lower base plate for lower beam	B3	bolts group for loading frame
		B18	top face in lower beam		
C	loading box	C1	end plate in box	C3a	thread hole
		C1a	waist-type hole	C3b	central hole
		C1b	threaded hole	C3c	waist-type hole
		C2	side plate in box	C4	anchor ear
		C2a	thread hole	C5	bolts group for anchor ear
		C2b	plain round hole	C6	pad
		C3	bottom plate in box	C7	lifting ring
D	steel band and affiliated components	D1	steel band	D6b	plain round hole
		D1a	central hole in steel band	D6c	thread hole
		D1b	processed end holes	D71	tensioned screw
		D2	face plate	D72	adjusting nut for tensioned screw

D3	nut	D73	big washer
D4	rock bolt	D81	stop screw
D5	pressing plate	D82	adjusting nut for stop screw
D51	plain round hole	D83	stop washer
D6	pulling plate	D9	locking bolt
D6a	thread hole		

3.2 Testing system assemblage and operation procedure

Based on respective drawings in Fig. 7 and the corresponding interpretations of the drawings, some photos showing the preparation process and the testing process are shown in Fig. 8. The detailed operation procedures are presented below.

First, the bolt is inserted into the central hole (C3b) in the bottom plate (C3) and its position is adjusted accordingly. Second, some cement blocks are prepared to simulate the blocky roof strata, as shown in Fig. 8a. Strata such as that with this pattern are quite common in the roofs of coal mine roadway, where the thickness is 120~150 mm. The cement blocks are prepared by randomly inserting the separation plates during the setting process, and the specific process is similar to the work conducted by (Shan et al., 2019). The uniaxial compressive strength of the cement can reach up to 60 MPa in seven days, which is strong enough to simulate the *in situ* roof strata. Third, some gravel with diameter ranges from 10 mm to 30 mm are paved on the top of the cement blocks, and the thickness is 50 mm or so, see Fig. 8b. Fourth, the top of the gravel layer is covered by a strap, then the face plate and the nut are installed accordingly (Fig. 8c); note that both nuts at the two ends of bolt are tensioned to some extent. Eventually, the entire system is removed to the loading space of the MTS machine, and the lifting rings (C7) could be helpful during removals. Fig. 8d exhibits how the system arranges itself with the loading plates of the MTS machine. It is worth mentioning that some buffering material should be placed between the baseplate (A1) and the baseplate in the lower beam (B14), thereby the abrupt drop of the loading frame (B) can be avoided due to potential tensile failure of the bolt during testing.

3.3 Parameters of the straps and bolting components

The bolts, collected from the Fujiaao coal mine, were cut out from a coal mine bolt from their respective threaded ends, with 18 mm diameters and 50 cm lengths. To install the nut on the other end of the bolt to tension the bolt during the test, a section 150 mm from the cutting end was lathed to form an approximately identical thread that is just similar to another end (original end).

The straps were collected from the Fujiaao coal mine and were cut into segments with a length of 50 cm and an unchanged width of 25 cm. The bolt hole was reserved at the centre of the strap segment, and the thickness of the straps was 3 mm. Three small end holes (D1b in Fig. 7j) were drilled at each end of the straps, thereby the movement of the ends can be prevented by the pressing plate (D5 in Fig. 7h) and the pulling plate (D6 in Fig. 7i), as has been formerly stated.

The face plate was also collected from the Fujiaao coal mine and was a domed face plate (DFP), as mentioned in section 2. The face plate was 120 mm in diameter and 10 mm thick. The face plate contacted the straps on the top of the face plate where a steel spacer was placed, then a pressure transducer was inserted through the bolt. Another steel spacer was placed on the top of the transducer, with a nut collected from the coal mine tightened there. The above arrangement can be seen in Fig. 8c.

3.4 Simulated scenarios

The mechanical behaviour of the strap is greatly influenced by the cracks and caved holes beneath it, especially for those distributed beneath the face plate, which will interrupt the load transfer between the bolting system and the rock mass, and the reinforcing zone of the bolting system will also be weakened. For the mechanical behaviour of strap to be recreated under such a loading environment, three scenarios were proposed, as shown in Fig. 9, and a relevant explanation is listed as below.

1. Cracked high-strength concrete blocks were overlaid by a gravelled layer. This scenario is quite similar to that described in Fig. 8a-b, where the gravel is set for simulating strata in the engineering field, where the surface layer of the rock is sensitive to water and then expresses a debris-like pattern. Sometimes this pattern can be noticed in areas where geological fault exists.
2. Compared with scenario 1, a circular hole is reserved in the centre of the upper layer (gravelled layer), the centre of the hole directly faces the hole of the strap and the face plate, with a hole diameter of 150 mm. This scenario was set for simulating an engineering situation where the surface rock mass is cracked and with the existence of caved holes beneath the face plate. It is worth noting that the inner wall of the circular hole can easily collapse under an extrusion force between the strap and simulated rock mass.
3. Compared with scenario 1, the gravelled layer was removed, and a circular hole was reserved at the centre of the concrete layer, and the diameter of the hole was 150 mm. Compared with scenario 2, the strength of the concrete blocks is much larger than that of gravel piles, so the inner wall of the circular hole is unlikely to collapse when the strap presses the concrete layer during the loading process.

4. Results And Analysis

4.1 Mechanical analysis

On the basis of the aforementioned loading equipment and simulated scenarios, three testing configurations were prepared and labelled as configuration #1, #2 and #3. The simulated roof condition

in configuration #1 is scenario #1 in Fig. 9. The same principle applies for configuration #2 and #3. Following the testing arrangement shown in Fig. 8d, the loading rate is set as 10 mm/min, then the obtained results are plotted in Fig. 10.

The peak loads and corresponding displacements at the peak load for configuration #1, #2 and #3 are 128.62 kN and 23.47 mm, 145.78 kN and 40.22 mm, and 140.43 kN and 67.67 mm, respectively. Before further interpreting the inner mechanism, it needs to be emphasized that the bolt inside the entire system mainly sustains tension with its two ends respectively locked by nuts. Therefore, the mechanical status of the bolt in the system is tension-dominated, which is similar to a pure tensile test on the bolt if the strength of the strap and the face plate are sufficiently large.

For configuration #1, the peak load is comparatively lower than that of system #2 and #3. The failure was actually induced by the slippage between the lower thread section and nut (see label D3 in Fig. 7d). In section 3.3, it was stated that the cutting end was lathed to form a thread so that the nut can be installed. However, compared with the thread rolling method applied on the original end during the bolts manufacturing procedure, the lathing method will weaken the tensile capacity of the bolt. Though the bolts in system #2 and #3 are also lathed, their failure was not caused by slippage between the thread and the nut, since the lathing sometimes was determined by human experience. The locking effects between the nut and thread are comparatively weak in configuration #1, and under the increasing load from the MTS machine, the nut will gradually slide along the thread, therefore some vibration in the load can also be observed at a later stage prior to the end of the curve. In Fig. 10b, a slippage trace can be noticeably seen in the lathed thread section of the rightmost bolt, the thread end of the bolt is the most susceptible part to fracturing (Kang et al., 2013).

As for system #2 and #3, both of their tests were eventually failed due to bolt tensile failure, with the failure patterns listed in Fig. 10b. It can be seen that the failure position is always in the lathed thread section. It can be seen that a yield state is missing along the loading curves in Fig. 10a. This is because a rupture always tends to occur somewhere in the lathed thread section, so a yield behaviour is difficult to notice. Nonetheless, the linearly increasing section and the necking section in Fig. 8a are relatively similar to those expressed in Fig. 10c.

In Fig. 10d the stiffness changing law is plotted. As seen, configuration #1 has the largest stiffness, and this value could have been larger if the failure of the system was not caused by a slippage between the thread and nut. Configuration #2 has a much smaller stiffness that is valued 3.62, which is a 33.9% drop compared with that of configuration #1. The falling range of configuration #3 is 62.2% compared with that of configuration #1, and the stiffness reads as 2.07.

In view of the results presented above, it can be concluded that the existence of the hole beneath the strap has a predominant impact on the mechanical behaviour of the bolt. For scenario #1, although the gravelled layer is comparatively loose and no tensile strength can be sustained, the compressive strength still exists. The anti-compression capacity enhances as the contact area between the pressing plate and gravel increases (in this test the pressing plate is a strap). Therefore, as long as the gravelled layer is

compact, the buckling of the strap can be avoided and the bearing capacity of the system is more likely to be determined by the strength of the bolt, face plate, or nut. This result is supported by field observations where some supporting system failed with a bolt rupture while the affiliated components were undamaged, as shown in Fig. 3a.

Alternatively, if a circular hole exists beneath the face plate, then the stiffness of the system will decrease accordingly, such as configuration #2 and #3 shown in Fig. 10d. The inner wall of the circular hole in scenario #2 is not stable because it was shaped by gravel, and the rigidity of the inner wall cannot be guaranteed when the strap sustains a load and some gravel near the circular hole tends to collapse. The collapsed gravel fills the gap beneath the face plate; as the load increases, the collapse degree also increases. Regardless, the reserved holes in scenario #2 leaves space for the strap to deform, especially for the area around the hole, thereby a relatively smaller stiffness is expressed, or an apparent sinking of the face plate is observable.

If the inner wall of the circular hole is rigid, such as the situation in scenario #3, then it is unlikely for the inner wall of the circular hole to collapse, and potential space for the strap to deform is sufficient. Under these circumstances, the shearing capacity of the strap becomes as a decisive factor that determines the system's stability, and the stiffness of the system is even smaller because of the sinking of the face plate. If the tensile strength of the bolt is sufficiently large, it is possible to lead a shearing failure on the strap, just as what is observed in engineering field (see Fig. 3e and Fig. 3f).

4.2 Deformation evaluation on the face plate and the strap

Two main failure inducements are the slippage between the bolt thread and nut, and the bolt rupture. Actually, the system consists of a strap, bolt, face plate, and nut. Even though the remainder of the components, apart from bolt, do not fail during the test, an investigation on their deformation characteristics is important for understanding the specific collaborative mechanism among them.

Fig. 11 lists the exact failure patterns for configuration #1~#3 after the test. For all configurations, the face plates barely express the deformation and no distortion can be observed. This strongly testified that the face plate utilized in the Fujiaao coal mine is absolutely reasonable, which is supported by a laboratory test on the DFP in section 2.5. In Fig. 6a, the peak load of the DFP is 369.49 kN, which is much larger than the tensile strength of the bolt, and the end point of the linearly increasing section is 229.52 kN, which is also much larger than the peak load (145.78 kN) in Fig. 10a.

Regarding the distortion of the strap, it can be seen from the figure that the strap in configuration #1 exhibits the smallest distortion, and only some small-scale bend can be seen (see Fig. 11a). Since no holes exist beneath the strap, the tensile force of the bolt will first be transferred to the face plate, which will then force the face plate to compress the strap along its outer edge. Even the outer edge facilitates the formation of a stress concentration ring on the strap, the gravel beneath the scope of the ring leaves no space for the circular area to sink, so the shearing stress on the concentration ring is actually co-sustained by the gravel and the strap. Therefore, only an indentation can be noticed on the strap after the

test (see Fig. 11b). It can also be seen that the strap is far from being sheared, the gravel beneath the scope of the indentation serves as a 'protector' to the strap. As a result, the bearing capacity of the supporting system is highly depended on the strength of the bolt.

For configuration #2, the strap distortion becomes obvious and apparent, especially for areas on the left side of the face plate (see Fig. 11c). The existence of a prepared hole beneath the centre hole of the strap makes the area beneath the stress concentration ring lose its 'protector', thereby leaving a comparatively larger space for the face plate to sink. However, as mentioned previously, the inner wall is not stable under the setting, hence a collapse of the hole is unavoidable, which will diminish the shearing stroke of the face plate and alleviate the strap distortion. For configuration #3, the inner wall of the pre-prepared hole is concrete, and the inner wall will not collapse if the load is appropriate. Then, the shearing stroke will not be diminished, eventually leading to an even more apparent distortion of the strap, as seen in Fig. 11d.

To evaluate the strap distortion in a more detailed measure, 3D scanning was conducted on all straps. All straps were first printed red to improve the recognition rate of the 3D scanning device. The printed straps are shown in Fig. 12a. The scanning system was invented by Creaform Inc. in Quebec, Canada. After scanning, the data were processed. The cloud maps are shown in Fig. 12b-d, through which the surface elevation at different points on the strap can be vividly judged.

The surface elevation map for the strap in configuration #1 is shown in Fig. 12b, the distortion field has a good symmetry property and the deep blue area indicates the indentation scope due to compression of the face plate. Overall, the distortion looks similar to the V-shaped fold proposed in section 2.2. The area nearby the top left corner has the highest elevation reads at roughly 64.40 mm. For the strap in configuration #2, the left section has a comparatively higher elevation and is characterized by an intense distortion, while the elevation variation in the right section is relatively gentle. Due to the previously mentioned collapse of the inner wall, the scope of the hole will be enlarged. Therefore, the sink scope will also be enlarged. This process contributes the large scope of the blue areas in Fig. 12c. The highest elevation is 115.5 mm obtained by the left centre edge of the strap, while the smallest elevation is located at the centre of the bolt hole. For the strap in configuration #3, the V-shaped fold distortion is more obvious (see Fig. 12d). The deep blue area, indicating a sink, is roughly rectangular-shaped, and the spreading scope is limited because the inner wall of the reserved hole is unlikely to collapse, as previously mentioned. The highest elevation is 128.5 mm, located at the left centre edge of the strap, which is the highest one for all configurations. For most of the right section, the distortion is obsolete, which is similar to the behaviour in Fig. 12c.

Obtaining the deformation data along a specific line along the strap surface is useful for better understanding the distortion details. To reach this goal, six monitoring lines in total are selected along the surface of the strap, of which three are horizontal monitoring lines along the length direction and another three are vertical monitoring lines along the width direction, as seen in Fig. 13. Line W2 and line L2 pass through the centre of the hole, variables a (b) respectively represent the horizontal (vertical) distance from the right (top) edge of the hole to the right (top) edge of the strap. In view of the definition, the position of

line L1 is defined at a distance of $a/2$ to the top edge of the strap, and the position of L3 is defined by setting line L2 as the axis of symmetry. In the same way, lines W1 and W3 can also be defined as shown in Fig. 13.

The monitoring results along the lines in Fig. 13 are listed in Fig. 14. Overall, the curves trend in Fig. 14 normally have a good consistency with the cloud views in Fig. 12. Along the length direction, the bending degree along a specific curve can be evaluated based on the slope of the curves in Fig. 14a, 16c and 16e. Taking curve L2 in each strap as an example, the slope of the left half can be calculated by defining the highest elevation and the lowest elevation. The selected parameters are shown in Table 2. Then, the slopes on the left half in the above figures are 0.133, 0.681, and 0.861, respectively. It can be seen that the strap bending in configuration #3 is the most obvious and that in configuration #1 it is obsolete. The reason leading to this result, refer to the relative explanation in Fig. 11.

In configuration #3, the space beneath the face plate provides an opportunity for the face plate to sink, therefore then folding trend is evident and the process is similar to folding a plastic board. Thereby the deformed elevation along the length direction is quite smooth, and the monitoring lines along different horizontal places exhibit no obvious difference with one another.

Along the width direction, W2 plays a key role as it passes through the centre of the hole and it closes to the position where the failure most likely to occur. In Fig. 14b, 16d and 16f, the overall elevation of W2 is always at the bottom, indicating serious sinking along this monitoring line, and vice versa for W1, which indicates apparent upward warping along the monitoring line. However, the elevation for W3 roughly portrays the transverse section line of the strap and the apparent deformation is not evident. W1 for straps in configuration #2 and #3 both express an arched bump at the centre of the curves, which is caused by the uneven distortion of the strap, which can also be reflected by cloud maps in Fig. 12c-d. More specifically, two convex vaults along the length direction of the strap increase the anti-deformation capacity of the strap, which makes the centre area more likely to bump. A relatively vertical distance among the curves can characterize the overall distortion degree, and the strap in configuration #3 is the most evident. The relevant mechanism has been previously stated.

Table 2 Parameters for slope calculation of L2 in each configuration

Configuration No.	Highest elevation (mm)	Length at the highest elevation (mm)	Hole edge elevation at the same side (mm)	Length at the hole edge (mm)	Slope
1	-205.31	13.11	-22.37	-11.16	0.133
2	-214.13	84.82	-52.47	-25.35	0.681
3	-158.35	86.6	-47.55	-8.77	0.861

4.3 Extended test on the square domed face plate

The face plates tested in the loading box are collected from the Fujiaao coal mine, and the square domed face plate (SDFP) mentioned in section 2.4 is not installed in the loading box. The SDFP is very familiar in most engineering fields, as most practitioners believe that it is able to spread the stress to the rock mass or the affiliated strap with remarkable effects, and its mechanical behaviour is better than that of the domed face plate (DFP).

In this section, the mechanical behaviours of the SDFP and DFP are compared. The parameters for the domed face plate are identical to the former test, the dimensions of the square domed face plate are 120*120 mm in edge length and 10 mm thick. For the strap, each end has three drilled holes that can be utilized to lock the ends with the loading box, then potential rising trend at the ends can be restricted by the pulling plate (D6), pressing plate (D5) and stop crew (D81) in Fig. 7. All of the loading conditions are unchanged.

The testing results are shown in Fig. 15. It can be seen that the loading relationship for the DFP configuration can be divided into two phases. The first phase is a slow increase of load at the beginning, and the second phase begins from the linear reaction. The mechanical behaviour of the second phase is dominated by the tensile property of the bolt by referring to its changing pattern. A linearly increasing process followed by a yield stage and then followed by a hardening stage and necking stage can apparently be seen. All of the characteristics are identical to the tensile test of the bolt, as seen in Fig. 10c. The overall adaptive subsidence of the strap plays a major role at the beginning. Afterwards, the mechanical response is jointly dependent on the tensile behaviour of the bolt and the sinking speed of the face plate.

For the SDFP configuration the curve can be divided into three stages. The first stage is quite similar to what is experienced for the DFP configuration, namely, a slow increase of the load, which can be attributed to the adaptive subsidence of the strap at the area where the SDFP extrudes. The second stage is a linear rising reaction between the displacement and the load. The main activity of the system at this stage is the partial elongation of the bolt under tension and a partial deformation of the strap. The third stage is the convex section along the curve, indicating a decreasing trend of the load increasing rate. The state is sustained until the peak load is reached, then the load decrease phase follows.

Regarding the specific parameters at the critical points, the yield point for the DFP configuration is reached with an approximate load of 125.09 kN at 27.96 mm, and the peak point is reached with a load of 146.97 kN at 38.84 mm, where the stiffness is 3.78. The peak load for the SDFP is 117.77 kN at 39.22 mm, and the stiffness is 3.00. Undoubtedly, this proves that the DFP has a higher strength and is more sensitive to a load increase, which is always favourable for a coal mine roadway support.

In Fig. 16, the photos showing the testing process and the results are exhibited. The strap distortion of the SDFP configuration is not very severe when compared with the strap distortion of the DFP configuration, as can be concluded by referring to Fig. 16a-b. Nonetheless, a sharp crack is noticed at the left edge of the bolt hole in the strap of the SDFP configuration (see Fig. 16a). The crack was actually caused by squeezing of the nut when the face plate was reversely deformed, as seen in Fig. 16d, with the original pattern before the test attached in Fig. 16c. In Fig. 16d, the face plate had been totally overturned and cracks are shown at positions bilateral to the nut. The reverse side is appended in Fig. 16e, and it can be seen that the cracks extended their paths from the edge of the hole to the edge of the face plate. The morphology of the concrete hole beneath the strap after the test is shown in Fig. 16. Although collapsed debris did exist, it did not impede the sinking of the face plate because the covering area of the SDFP was barely deformed (see indentation in Fig. 16a). Overall, the displacement order from large to small that occurred on the SDFP configuration is distortion of the face plate, strap deformation, and bolt elongation.

The strap distortion for the DFP configuration is severe and the middle right section is extremely warped; the pattern looks similar to the multiple fold type proposed in Fig. 2. Even though the DFP barely expressed any sign of deformation damage, it is reasonable when considering the bearing capacity of the DFP in Fig. 6a. The displacement that occurred on the DFP configuration is mainly contributed by the sinking of the DFP or distortion of strap, additionally with a small contribution from the bolt elongation.

A cloud diagram revealing the surface elevation of the strap in the SDFP configuration is shown in Fig. 17a. The results of the DFP configuration are not presented due to the overlapping distortion at the middle right area (see Fig. 16b). In Fig. 17a, most areas on the surface of the strap express no apparent distortion, except for the centre area, left bottom part and right bottom part. The lower distorted part exhibits a warping trend with a maximum value of 75-85 mm. The centre area behaves with the lowest elevation and the outmost contour line in this area is quite similar to the size of the square domed face plate, namely, 120*120 mm in length and width, respectively. To be more specific, the oval-shaped blue area at the centre indicates a severe sinking and is influenced by the sinking of the nut at a later stage.

Following the same principles defined in Fig. 13, the monitoring results are presented in Fig. 17b-c. Unlike what presented in Fig. 14, the wrapping at the ends of the strap were largely restrained due to the locking effects through the pre-drilled holes (Fig. 17b). The centre section, ranging from approximately -90 mm to 90 mm, experiences a concave trend, which is caused by the SDFP sinking. Comparatively, a higher elevation at the two ends of L3 is consistent with the red- areas in Fig. 17a. From the width monitoring results, it can be seen that distortion along W1 and W3 is negligible and the cross section of the W strap is not largely impacted. Therefore, the locking effects mentioned above are useful in controlling the wrapping tendency during loading. The middle section of W2 has the lowest elevation due to the sinking of the SDFP.

5. Discussion

Assisted by the designed loading box, the loading system among the bolt, face plate, and strap was recreated with a high similarity to the *in situ* situation. An interesting result from the test is that it strongly refutes the theoretical viewpoint proposed in section 2.4. It was initially considered that the domed face plate was not suitable for cooperating with the strap due to the ring-aligned stress between the edge of the face plate and the strap; the stress concentration would probably cause the face plate to penetrate the strap, similar to what occurred in Fig. 3. Moreover, it was initially believed that the square domed face plate behaved much better than the domed face plate and the stress distribution assumed in Fig. 4 supported such an ideology; the flat area around the domed sphere could avoid a stress concentration due to its face contact with the strap. Although the numerical and preliminary laboratory tests on face plates have already given some verdicts, a combination supporting a form similar to the *in situ* situation is conducted to find more evidence. Under the same loading conditions, the domed face plate is beneficial for the overall stability of the supporting system, and the square domed face plate is easy to wrap under a high force from the bolt due to the small diameter of the sphere area. Thereby, the disadvantages of the square domed face plate are proven.

As for what occurred to the strap in Fig. 3e-f, it was not recreated in the laboratory. By moving attention to the corrosion state of the strap in Fig. 3, an interesting phenomenon is noticed: straps with a shearing hole are all highly corroded (see Fig. 3e and Fig. 3f). Hence, strap corrosion should be one of the essential factors for the face plate to share through the strap. Although the straps in Fig. 3b and Fig. 3d are also highly corroded, the mechanism is different. For strap in Fig. 3b, indentation indicates a certain compression force between the strap and the face plate. However, the face plate is not able to shear through the strap because of the compact rock mass beneath the strap, which is similar to how configuration #1 behaves in Fig. 11a-b. Considering the corrosion environment at this place, a bolt failure was also caused by the corrosion, and the corrosion on the strap continued after the bolt failure. For the strap in Fig. 3d, there is no indentation on the surface, indicating that there is no compression force between the face plate and strap, therefore shearing through the strap by the face plate was also unlikely to occur.

To quickly summarize, three preconditions must exist for the strap to be sheared through by the face plate: 1) the bolting system should be reliable, so decoupling, rupture, thread failure, nut failure, etc., should not occur in order to guarantee the high compression force between the strap and the face plate. 2) A cavity or extrusion space must exist beneath the hole of the strap or face plate, therefore enough sinking displacement is allowed for the face plate; if the rock is sometimes brecciated but still compacted, then it is still unlikely for the face plate to sink. 3) If environmental corrosion exists, either underwater corrosion or stress corrosion cracking, then the chances for the strap to be sheared through can be increased dramatically. 4) Pulling the effects from neighbouring supporting elements is a must, for example, the pinning effects of a cable bolt or rock bolt, thereby avoiding warping of the strap bilateral to the potential shear zone.

Readers may oppose the above verdicts because one end of the bolt utilized in the loading box was lathed and the tensile strength was weakened; otherwise, maybe the strap could have been sheared

through by the face plate, as shown in Fig. 3e-f. Nonetheless, from Fig. 10a it can be seen that the ultimate load for configuration #2 is 145.78 kN, which is quite close to the ultimate load of the tensile test on the bolt, as exemplified in Fig. 10c. Even though the strap in configuration #2 was far from being sheared through and no trace of crack or torsion was found near where the face plate pressed. Enlarging the bolt diameter may lead to a different result, and a possibility does exist for the strap to be sheared through. The authors hope to research this in the future due to limitations of this paper.

Another query of this study is that the S-shaped fold, Z-shaped fold, and multiple fold of the distorted strap, as listed in Fig. 2, did not fully appear in the laboratory. Though V-shaped fold or inverted V fold distortion in field observations is similar to the strap distortion exhibited in Fig. 11 and Fig. 16, it should be noticed that this distortion in the laboratory was caused by vertical loading in the bolt. In the engineering field, the V-shaped fold or inverted V fold distortion can be the result of many aspects, such as ribs movement, unbalance roof subsidence, and pulling the effects of the neighbouring supporting units. Until now, it has still been difficult to absolutely recreate the movement of a rock mass in the engineering field. The loading box designed in this study can only apply a vertical load to the simulated supporting system; unbalanced loading, such as rib movement or roof extrusion in the engineering field, cannot be simulated. The unbalanced loading requires a loading box characterized by various loadings from different directions, and the effectiveness is limited considering the relevant complications and costs.

This study also raises a rethinking of the effectiveness of field observations or empiricism-oriented design in coal mine roadway support. A human's past experience oftentimes is very important to ensure an engineering success; nonetheless, humans are not a programmed machine and mistakes do occur frequently if insufficient patience and preciseness are given prior to implementation. A satisfactory support system should have compatible supporting components, both in terms of load and deformation capacities, thereby an optimum reinforcement effect is expected to be achieved (Li, 2017).

6. Concluding Remarks

The primary objective of this study was to investigate the failure mechanism of W straps in coal mine roadway supports and to discuss the cooperation mechanisms with different types of face plates by laboratory tests and numerical simulation. The main conclusions are stated below.

- Using the Fujiaao coal mine as an engineering example, the failure characteristics of W straps were analysed based on field observations. Essentially, the failure patterns are classified as either a S-shaped fold, Z-shaped fold, V-shaped fold, inverted V fold, or multiple fold. These types are representative and can correspond with most of the *in situ* failure patterns of the straps.
- A hypothesis was proposed based on field observations, which interprets the shearing through mechanism of straps due to the compression of the face plate. It was believed that the circular distributed stress concentration caused by the edge of the domed face plate was the leading reason for shearing through the strap, and a traditional square face plate is believed to be efficient in solving

the problem. A subsequent numerical simulation and laboratory test on a traditional square domed face plate and a domed face plate presented another verdict that conflicts with the hypothesis.

- A loading apparatus was designed that is able to recreate the mechanical state of straps in coal mine supports. The distortion characteristics of the strap were thereby analysed and compared with those observed in the engineering field. Different conditions of the rock mass beneath the strap were simulated, which demonstrated that the bolt tensile rupture was the main cause in most circumstances and that the bottleneck problem is the thread section along the bolt. A noteworthy verdict is that fragmentized rock may not be detrimental to the distortion of the strap, as long as the rock is kept in contact. If a rigid cavity exists beneath the strap and only the face plate presses the cavity, then distortion could occur immediately.
- A laboratory test on a square domed face plate and a domed face plate corrected the proposed hypothesis and testified the righteousness proposed in the numerical simulation. Although the domed face plate has a sharp edge and was initially believed to be harmful to the strap, the warping of the square domed face plate is much more harmful and it loses bearing capacity immediately after warping. In contrast, the comparatively higher anti-warping capacity of the domed face plate is favourable for reaching a higher bearing state as long as the rock mass beneath it is intact.
- The laboratory tests failed to recreate the shearing through of the strap that occurred in the engineering field. Environmental corrosion is speculated to be the main reason for this phenomenon, as can be proven by field observations. Under the additional impact of stress, it is very likely for the face plate to shear through the strap.

Declarations

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Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

Data availability

The raw data used to support the figures in this study may be shared from the corresponding author upon request.

Authors' contributions

Xiaowei Feng proposed the idea, conduct part of the experiment, wrote the manuscript. Fei Xue and Qun Wei jointed the experiment and processed the data.

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Figures

Figure 1

Supporting effects comparison for a bolt, a mesh+bolt, and a mesh+strap+bolt

Figure 1

Supporting effects comparison for a bolt, a mesh+bolt, and a mesh+strap+bolt

Figure 2

Supporting effects comparison for a bolt, a mesh+bolt, and a mesh+strap+bolt

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Supporting effects comparison for a bolt, a mesh+bolt, and a mesh+strap+bolt

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Supporting effects comparison for a bolt, a mesh+bolt, and a mesh+strap+bolt

Figure 3

Overall distortions of W straps based on in situ observations in the Fujiaao coal mine

Figure 3

Overall distortions of W straps based on in situ observations in the Fujiaao coal mine

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Overall distortions of W straps based on in situ observations in the Fujiaao coal mine

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Overall distortions of W straps based on in situ observations in the Fujiaao coal mine

Figure 4

Detailed failure patterns of the strap-bolt supporting system

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Detailed failure patterns of the strap-bolt supporting system

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Overall distortions of W straps based on in situ observations in the Fujiaao coal mine

Figure 4

Overall distortions of W straps based on in situ observations in the Fujiaao coal mine

Figure 4

Supporting effects comparison for a bolt, a mesh+bolt, and a mesh+strap+bolt

Figure 4

Detailed failure patterns of the strap-bolt supporting system

Figure 5

Stress distribution between the face plate and strap for different types

Figure 5

Stress distribution between the face plate and strap for different types

Figure 5

Detailed failure patterns of the strap-bolt supporting system

Figure 5

Stress distribution between the face plate and strap for different types

Figure 5

Detailed failure patterns of the strap-bolt supporting system

Figure 6

Overall distortions of W straps based on in situ observations in the Fujiaao coal mine

Figure 6

Stress distribution between the face plate and strap for different types

Figure 6

Stress distribution between the face plate and strap for different types

Figure 6

Stress distribution between the face plate and strap for different types

(a)

(b)

Figure 6

Compression test results on the domed face plate and square domed face plate

Figure 6

Numerical simulation results for the square domed face plate and domed face plate

Figure 7

Detailed failure patterns of the strap-bolt supporting system

Figure 7

Detailed failure patterns of the strap-bolt supporting system

Figure 7

Detailed failure patterns of the strap-bolt supporting system

Figure 7

Stress distribution between the face plate and strap for different types

Figure 7

Detailed failure patterns of the strap-bolt supporting system

Figure 7

Schematic drawings of the loading equipment. (a) Overall diagram for the loading equipment, (b) overall diagram for the pedestal, (c) overall diagram for the loading frame, (d) cross-section diagram along the transverse centre plane in (a), (e) cross-section diagram along the longitudinal centre plane in (a), (f) overall diagram for the loading box with the steel band installed, (g) overall diagram for the empty loading box, (h) detail of a plate with holes, (i) detail of a plate with holes, (j) detail of a plate with holes.

loading box, (h) diagram for the pressing plate, (i) diagram for the pulling plate, and (j) diagram for the processed steel band.

(a)

(b)

Figure 8

Compression test results on the domed face plate and square domed face plate

Figure 8

Numerical simulation results for the square domed face plate and domed face plate

Figure 8

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

Figure 9

Stress distribution between the face plate and strap for different types

(a)

(b)

Figure 9

Compression test results on the domed face plate and square domed face plate

Figure 9

Stress distribution between the face plate and strap for different types

(a)

(b)

Figure 9

Compression test results on the domed face plate and square domed face plate

Figure 9

Schematic drawings of the loading equipment. (a) Overall diagram for the loading equipment, (b) overall diagram for the pedestal, (c) overall diagram for the loading frame, (d) cross-section diagram along the transverse centre plane in (a), (e) cross-section diagram along the longitudinal centre plane in (a), (f) overall diagram for the loading box with the steel band installed, (g) overall diagram for the empty loading box, (h) detail of a plate with holes, (i) detail of a plate with holes, (j) detail of a plate with holes.

loading box, (h) diagram for the pressing plate, (i) diagram for the pulling plate, and (j) diagram for the processed steel band.

(a)

(b)

Figure 9

Compression test results on the domed face plate and square domed face plate

Figure 9

Detailed failure patterns of the strap-bolt supporting system

Figure 9

Numerical simulation results for the square domed face plate and domed face plate

Figure 10

Schematic drawings of the loading equipment. (a) Overall diagram for the loading equipment, (b) overall diagram for the pedestal, (c) overall diagram for the loading frame, (d) cross-section diagram along the transverse centre plane in (a), (e) cross-section diagram along the longitudinal centre plane in (a), (f) overall diagram for the loading box with the steel band installed, (g) overall diagram for the empty loading box, (h) detail of a component with holes, (i) detail of a component with holes, (j) detail of a component with holes.

loading box, (h) diagram for the pressing plate, (i) diagram for the pulling plate, and (j) diagram for the processed steel band.

Figure 10

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

Figure 10

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

Figure 11

Stress distribution between the face plate and strap for different types

Figure 11

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

Figure 11

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

Figure 11

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

Figure 12

Numerical simulation results for the square domed face plate and domed face plate

Figure 12

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

Figure 12

Compression test results on the domed face plate and square domed face plate

(a)

(b)

Figure 12

Compression test results on the domed face plate and square domed face plate

(a)

(b)

Figure 12

Compression test results on the domed face plate and square domed face plate

(a)

(b)

Figure 12

Compression test results on the domed face plate and square domed face plate

Figure 12

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

Figure 13

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

Figure 13

Distortion patterns for straps in the loading box (label C in Fig. 7)

Figure 13

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

Figure 13

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

Figure 13

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

Figure 13

Distortion patterns for straps in the loading box (label C in Fig. 7)

Figure 13

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

Figure 14

Schematic drawings of the loading equipment. (a) Overall diagram for the loading equipment, (b) overall diagram for the pedestal, (c) overall diagram for the loading frame, (d) cross-section diagram along the transverse centre plane in (a), (e) cross-section diagram along the longitudinal centre plane in (a), (f) overall diagram for the loading box with the steel band installed, (g) overall diagram for the empty loading box, (h) detail of a plate with holes, (i) detail of a plate with holes, (j) detail of a plate with holes.

loading box, (h) diagram for the pressing plate, (i) diagram for the pulling plate, and (j) diagram for the processed steel band.

Figure 14

(a) Load-displacement relationship for specimen Nos. 1~3, (b) failure patterns of some representative bolts, (c) a typical deformation-load relationship of an 18 mm bolt under tensile test, (d) stiffness decreasing trend for configuration #1~#3.

(a)

(b)

(c)

(d)

Figure 14

Photos for distorted straps of configuration #1~#3 and their cloud views

(a)

(b)

Figure 14

Compression test results on the domed face plate and square domed face plate

Figure 14

(a) Load-displacement relationship for specimen Nos. 1~3, (b) failure patterns of some representative bolts, (c) a typical deformation-load relationship of an 18 mm bolt under tensile test, (d) stiffness decreasing trend for configuration #1~#3.

Figure 15

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

Figure 15

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

Figure 15

Distortion patterns for straps in the loading box (label C in Fig. 7)

Figure 15

Distortion patterns for straps in the loading box (label C in Fig. 7)

Figure 15

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

Figure 15

Definitions of the monitoring lines on the surface of the strap

Figure 15

Definitions of the monitoring lines on the surface of the strap

Figure 15

Distortion patterns for straps in the loading box (label C in Fig. 7)

Figure 15

Preparation procedure of testing system (a-c) and arrangement of the loading apparatus with the MTS machine (d)

(a)

(b)

(c)

(d)

Figure 16

Photos for distorted straps of configuration #1~#3 and their cloud views

Figure 16

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

Figure 16

Distortion patterns for straps in the loading box (label C in Fig. 7)

Figure 17

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

Figure 17

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 17

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

Figure 17

Simulated roof types, #1 cracked concrete blocks overlaid by the gravelled layer, #2 circular hole reserved in the centre of the upper gravelled layer, #3 circular hole reserved in the centre of the concrete layer.

(a)

(b)

(c)

(d)

Figure 17

Photos for distorted straps of configuration #1~#3 and their cloud views

Figure 17

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 18

Definitions of the monitoring lines on the surface of the strap

Figure 18

Definitions of the monitoring lines on the surface of the strap

Figure 18

Definitions of the monitoring lines on the surface of the strap

Figure 18

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

Figure 18

Definitions of the monitoring lines on the surface of the strap

Figure 18

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

Figure 18

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

Figure 18

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

Figure 18

Monitoring results along the length lines and width lines for the straps in configuration #1 (a-b), #2 (c-d) and #3 (e-f).

Figure 18

Definitions of the monitoring lines on the surface of the strap

Figure 18

Definitions of the monitoring lines on the surface of the strap

Figure 19

Distortion patterns for straps in the loading box (label C in Fig. 7)

(a)

(b)

(c)

(d)

Figure 19

(a) Load-displacement relationship for specimen Nos. 1~3, (b) failure patterns of some representative bolts, (c) a typical deformation-load relationship of an 18 mm bolt under tensile test, (d) stiffness decreasing trend for configuration #1~#3.

Figure 19

Distortion patterns for straps in the loading box (label C in Fig. 7)

Figure 19

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 19

Distortion patterns for straps in the loading box (label C in Fig. 7)

(a)

(b)

(c)

Figure 19

(a) Scanned cloud view of strap distortion in the SDFP configuration, in mm, (b-c) monitoring results along the predefined length lines and width lines for the strap in the SDFP configuration

Figure 19

Distortion patterns for straps in the loading box (label C in Fig. 7)

(a)

(b)

(c)

(d)

Figure 20

Photos for distorted straps of configuration #1~#3 and their cloud views

Figure 20

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 20

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 20

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

Figure 21

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

Figure 21

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

(a)

(b)

(c)

Figure 21

(a) Scanned cloud view of strap distortion in the SDFP configuration, in mm, (b-c) monitoring results along the predefined length lines and width lines for the strap in the SDFP configuration

Figure 22

Definitions of the monitoring lines on the surface of the strap

Figure 22

Definitions of the monitoring lines on the surface of the strap

Figure 23

Monitoring results along the length lines and width lines for the straps in configuration #1 (a-b), #2 (c-d) and #3 (e-f).

Figure 23

Monitoring results along the length lines and width lines for the straps in configuration #1 (a-b), #2 (c-d) and #3 (e-f).

Figure 25

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 26

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 26

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 26

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 26

Relationship between the displacement and load for a square domed FP (face plate) and domed FP

Figure 27

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

Figure 28

Test photos for the mechanical comparison between the SDFP and DFP. (a) Strap distortion of the SDFP configuration, (b) strap distortion of the DFP configuration, (c) SDFP configuration before the test, (d) failure pattern of the SDFP configuration after the test, (e) wrong side of the SDFP after test, (f) breakage pattern of the simulated square hole after the test.

(a)

(b)

(c)

Figure 30

(a) Scanned cloud view of strap distortion in the SDFP configuration, in mm, (b-c) monitoring results along the predefined length lines and width lines for the strap in the SDFP configuration