



Experimental Study on the Mechanical Behavior of Rock Bolts Subjected to Complex Static and Dynamic Loads

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Abstract

In underground mining practice, the rock bolt support system is the major support pattern to control the deformation and stability of openings. A rock bolt is generally subjected to complex loads including tension, torsion, bending and shear, which result from the deformation of excavations and exposure to dynamic loads that are generated by rockbursts. An understanding of the response of rock bolt under complex conditions is of great importance for rock bolt support design and practice. New sophisticated equipment has been developed for this purpose. This work involved a comprehensive experimental study on the mechanical behavior of rock bolts under complex loads. The results show that rock bolt pre-tensioning by torque application to the nut can result in decreases in tensile strength and elongation because the rock bolt is subjected to a combination of tension and distortion. When a pre-tensioned rock bolt is subjected to a shear load, the maximum shear force can reach up to 80% of the tensile capacity of the rock bolt. Higher impact energy results in a longer period of dynamic loading and a larger irreversible plastic deformation on the rock bolt, in contrast to a rock bolt that is subjected to low impact energy. The capacity and especially the deformation capacity of a rock bolt may decrease significantly after successive containment of the deformation of the surrounding rock mass from rockbursts.

Keywords Rock bolt · Mechanical behavior · Test equipment · Static–dynamic loading

1 Introduction

The rock bolt support is the main support pattern for coal mine roadways in China and is important in the construction and production of safe and efficient mines. With an increase in mining depth, the number of roadways that experience high stresses and coal bursts has increased significantly. As the mining intensity increases, the influence of mining-induced stress on roadway increases greatly, resulting in a large deformation of the surrounding rock and serious dynamic disasters. New challenges occur in rock bolt supports with the most prominent being significant deformation and damage of rock bolt system accessories.

Resin-anchored rock bolt are used extensively in Chinese coal mine practices. They tend to consist of rebar, bearing

plates, nuts, washers, and resin cartridges. Field investigations of the failure conditions of rock bolts in more than ten mining districts in China showed four locations that are susceptible to fracture: the contact between the thread, the contact between the rebar and the borehole collar, the interface between the free and anchored part, and position of intersecting rock joints (Kang et al. 2013). Of these, the thread is most vulnerable.

Three main reasons exist for rock bolt failure. (1) The mechanical properties of the rebar do not meet the requirements of large deformation; (2) cracks and damage occur during machining because of poor quality control, and thus the strength and deformability of the thread segment is reduced significantly; and (3) complex stresses are experienced by the bolt, and the poor matching of the accessories results in stress concentration and deformation localization. Bolt failure from the first two reasons can be solved by improving the material and processing technology and rebar equipment (Kang et al. 2009), and the third issue can be addressed only by understanding the stress state and the deformation and failure mechanism of the rock bolt.

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In underground mining practice, a rock bolt is subjected to combined loads, including tension, bending, shearing, torsion, and sometimes dynamic loads that result from coal bursts. Many studies have been conducted to evaluate the mechanical response of rock bolts under pure tensile conditions using pull-out tests. For example, Farmer (1975) performed pull-out tests on rock bolts in the laboratory and found that the axial force decreased exponentially from the point of loading to the far end of the bolt. Dunnam (1976) carried out pull-out tests on specimen anchorages to examine the mechanism of anchorage failure and proposed a formula to calculate shear stress at the steel/resin interface. The effect of factors, including the bolt profile, diameter, length and the mechanical properties of grouting materials on the pull-out load have also been examined (Kilic et al. 2002, 2003; Karanam and Dasyapu 2005). After evaluating the behaviour of fully grouted rock bolts in the Kielder experimental tunnel, Freeman (1978) stated the concept of “neutral point”, “pick-up length” and “anchor length”. The neutral point on a rock bolt exists where the shear stress on the bolt-grout interface is zero and the tensile axial load is at a peak. Björnfort and Stephansson (1984) found that in jointed rock masses, the opening of individual joints may result in several neutral points along with the bolt.

The behaviour of rock bolts under a shear load has also been extensively examined (Spang and Egger 1990; Ferrero 1995; Pellet and Egger 1996; Grasselli 2005; Jalalifar et al. 2006). Many laboratory and field tests were performed by Spang and Egger (1990) to evaluate the behaviour of fully-grouted, tensionless rock bolts in stratified and jointed rock masses. Spang and Egger (1990) proposed formulae to calculate the bearing capacity of fully grouted bolts. Using experimental measurements and numerical modelling, Ferrero (1995) proposed two failure patterns for rock bolts, which depend on the strength of the rock mass within which the rock bolt is installed. Pellet and Egger (1996) proposed an analytical model to predict the contribution of a rock bolt to the shear strength of a rock joint. The effects of bolt inclination, bolt mechanical properties, rock strength, and joint friction angle on the shear strength of rock joint were examined using the proposed model. By performing experimental tests and numerical simulations, Grasselli (2005) examined the mechanical behaviour of Swellex bolts and fully grouted bolts under shear conditions and found that the two bolt types deform differently. Jalalifar et al. (2006) developed a double shearing apparatus to examine the shearing behaviour of a bolt that was installed at a perpendicular angle cross two joints. They found that the bolt profile configuration, rock strength, and bolt pretension have a significant influence on the behaviour of the rock bolt that is subjected to shear. Based on field investigations of the failure state of rock bolts in underground high-stress conditions, Li (2010) found that the bolt failure tends to be caused by combined tensile and shear loads. Rock bolt failure may occur at the tail of the bolt or at

a certain distance from the bearing plate. Kang et al. (2015, 2016) conducted comprehensive and systematic studies on the mechanical response of a rock bolt and its accessories under varying loading conditions including tension, bending and twisting, which provides insight into the failure mechanism of rock bolts.

As the mining depth increases, dynamic rock failure (i.e., rockbursts, coal bursts) occurs more frequently and the severity increases significantly. An understanding of the mechanical behaviour of rock bolts under dynamic load is of great importance. The laboratory drop weight test is probably the most widely used mechanical characterization method (Yi and Kaiser 1994; Ortlepp and Stacey 1998; St-Pierre et al. 2007, 2009; Li and Doucet 2012). St-Pierre et al. (2009) carried out drop weight test on the tapered bolt and found that the drop hammer impact speed is a key factor that affects the bolt deformation. Momentum is the most effective index to evaluate whether the bolt is damaged under impact load. Gaudreau (2004) performed a cyclic drop test on the improved tapered bolt and found that the bolt does not undergo plastic deformation after the first impact load and reaches the yield point of the bolt. After many drop tests on the D-bolt, Li and Doucet (2012) found that the D-bolt showed a linear relationship between the extension and the impact energy under the impact load. The energy absorption effect of the D-bolt depends on the cross-sectional area, the tensile strength, and the bolt elongation. Using the Western Australian School of Mines (WASM) Dynamic Test Facility, Player (2012); Player et al. (2004) performed a series of dynamic tests on a threadbar reinforcement system and found that many factors have a considerable effect including embedment, decoupling, confinement, surface hardware and steel grade.

Nearly all studies were performed without the rock bolts being loaded or the rock bolts were tensioned only prior to the dynamic load. Limited research has been performed where the rock bolt is subjected to realistic complex loads before a dynamic load is applied. This occurs mainly because of a lack of equipment to conduct such tests. Recently, new sophisticated equipment has been developed in the Key State Laboratory of Coal Mining and Clean Utilization (KSLCMCU), China to test the mechanical behavior of rock bolt that were subjected to complex static and dynamic loading. Using this equipment, a comprehensive experimental study was performed on several rock bolts under various loading conditions.

2 Developed Equipment for Testing Rock Bolts in Complex Loads

2.1 Equipment Structure and Function

Figure 1 shows the developed equipment for testing rock bolts under complex loading conditions. The equipment

consisted of a bolt installation unit, a loading unit, an impact pendulum, a measurement system, and a console. The mechanical response of a rock bolt was monitored during installation, pre-tensioning, and any arbitrary loading combination of tension, torsion, bending, shear, and impact.

The installation unit was used to install a resin-anchored rock bolt into a reserved borehole drilled in a 1.2-m-long concrete column that was used to simulate rock. A major part of the concrete column (1 m long) was placed in a circular steel container that was placed horizontally in the equipment. A short part of the concrete column (0.2 m long) was placed in another cylinder container and formed a rock

joint for the shear test, see Fig. 1b. The gap between the two concrete columns was ~5 mm. Resin encapsulation was implemented in the borehole and the rock bolt was installed using the installation unit. The rock bolt was not anchored in the short concrete column. Therefore, shear sliding occurred at the boundary of the free and anchored sections of the rock bolt. During installation, the torque, propulsion speed, and the pushing force were measured. Pre-tension was applied to the bolt by tightening the nut.

In underground coal mining practice, rock bolts tend not to be installed perpendicular to excavation surfaces, but rather, they are installed at an inclined angle because of the

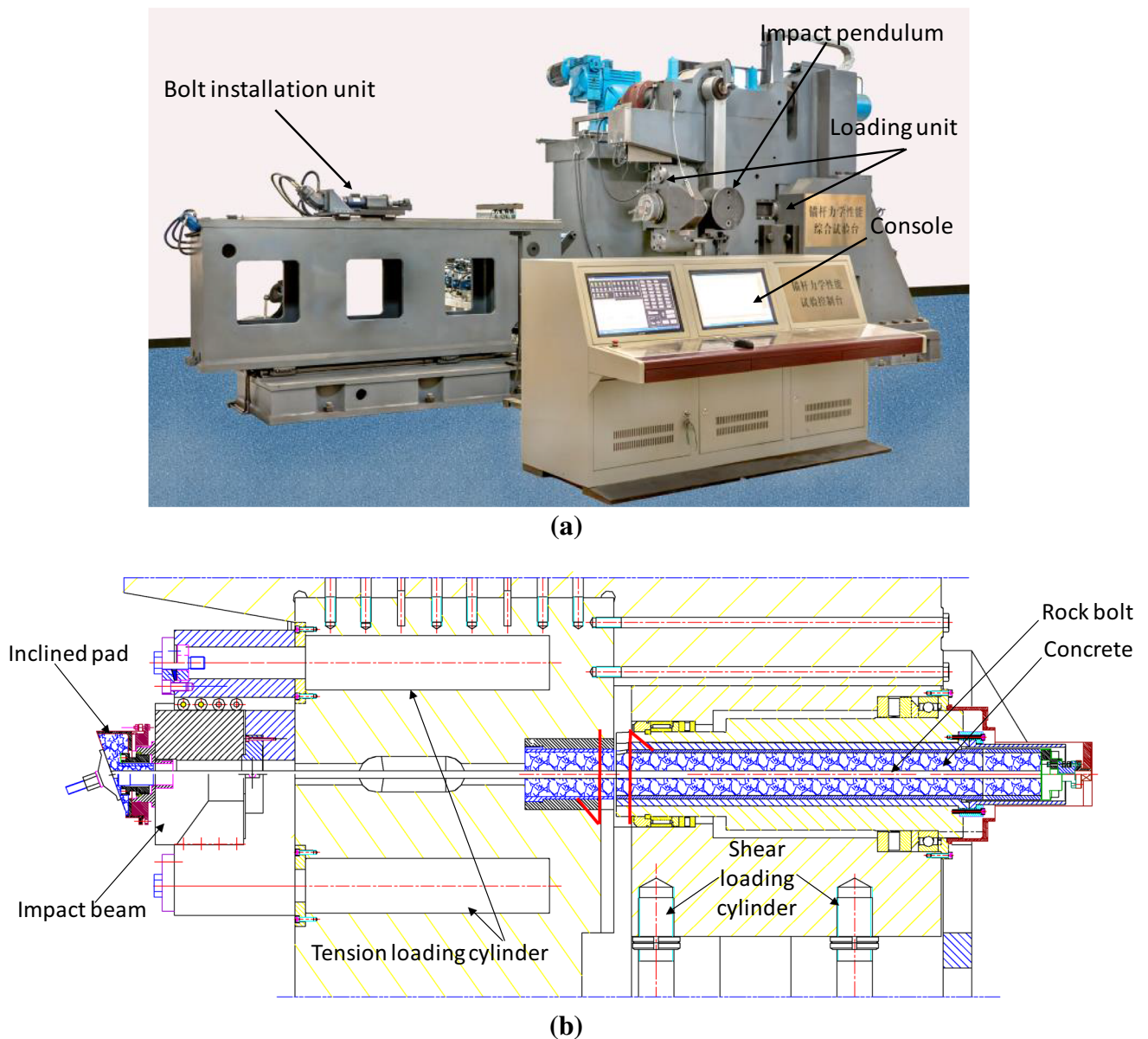


Fig. 1 Developed equipment for testing rock bolt under complex loads including tension, torsion, bending, shear, and impact. **a** Photos of the equipment, **b** design diagram of the equipment

rough excavation surface. Rock bolts at the corner of rectangular roadways tend to be installed at a large inclined angle because of difficulties of drilling vertically perpendicular to the roadway surface. This inclination may cause localized bending stress development in the thread end of the bolt when pre-tension is applied or when the surrounding rock deforms. To produce this bending state, an inclined pad with a certain angle is arranged at the tail of the bolt to simulate the inclination between the bolt and the excavation surface. In this way, after installation, the rock bolt has already been subjected to bending and torsion. Tension and shear loads can then be applied to the bolt to simulate the inward deformation of the excavation surface and sliding along joints. Tension is applied using two loading cylinders that are located symmetrically at the two sides of the rock bolt, see Fig. 1. The shear test was achieved by pushing the circular steel container upward within which the rock bolt was anchored using two loading cylinders, see Fig. 1.

An impact load was applied using an impact pendulum that was raised at a given angle and then falls to impact a beam behind the bearing plate through which the impact load was transferred to the rock bolt. The angle between the pendulum rod and the vertical line determines the impact energy after the pendulum falls. Different angles of the pendulum can be set to generate different impact energies.

Table 1 lists the loading capacity of the developed equipment.

The measuring system consists of various sensors types, a controlling computer and an automatic data acquisition system. The sensors include a dynamic torque sensor in the installation unit; a static torque sensor installed at the bottom of the cement column container; a displacement sensor placed at the anchored section; an axial displacement sensor mounted at the bearing place; a radial displacement sensor placed at the shear slider; a static load sensor between the impact beam and the tension beam; two static load sensors at the borehole collar and the end of the anchored section respectively; an axial acceleration sensor installed on the impact beam; and a dynamic load sensor placed at the thread

end of the bolt. The load control was executed automatically by the computer program software after the instruction was issued. Test data acquisition was achieved using a data acquisition card to transfer data between the sensors and the computer. All the data were recorded automatically in real time using computer program software. The load control system was divided into seven controllable loading modules according to the characteristics of each stage of the test process, namely, “anchor”, “pre-tighten”, “pull-out”, “shear”, “pull-out and shear”, “impact” and “manual”. All the monitored data were restored automatically in text files.

2.2 Rock Bolts Used for Testing

A series of experiments was carried out on rock bolts using the developed equipment. All the tested rock bolts and accessories, including the bearing plates, washers, and resin encapsulations were obtained from a rock bolt manufacturer in Shanxi, China. The rock bolts were high-strength left-handed and non-longitudinal rebar with the following properties: a 550-MPa yield strength; a 720-MPa tensile strength; 22% elongation at break; and a 22-mm diameter, 3-m length, and 150-mm long M24 thread. The bearing plates were arched with a size of 150 mm × 150 mm × 10 mm and a spherical washer. The rock bolt was anchored using two resin encapsulations with Z2335 specification (23 mm diameter and 35 mm length) and Z2360 (23 mm diameter and 60 mm length), respectively, which lead to an anchoring length of ~1.2 m. The uniaxial compressive strength of the concrete column was 22.4 MPa, which was equivalent to the strength of hard coal. The borehole diameter was 30 mm, and the inner and outer diameters of the steel container were 120 mm and 138 mm, respectively.

3 Mechanical Behavior of Rock Bolts Subjected to Complex Loading

3.1 Stress State of Rock Bolts After Installation

The initial stress state of a rock bolt after installation is the basis of the subsequent action of other loads caused by the deformation of the anchored rock mass. When a nut of a rock bolt is tightened during installation, then part of the torque acts on the rebar, and the other part acts on the interface between the nut end surface and the washer. This tightening results in a combined tension (i.e., the pretension of the rock bolt) and distortion suffered by the rebar. To evaluate the initial stress state, the tension and torque of the rebars were monitored during rock bolt installation. The applied nut torque was set to 120, 250, 350, and 450 N m. The torque that was applied to the nut does not equal to the designed value because the equipment was not servo-controlled. The

Table 1 Loading capacity of the developed equipment

No.	Loading items	Unit	Capacity
1	Pushing speed of bolt installation	mm/s	8–80
2	Pushing force of bolt installation	kN	0–15
3	Rotating speed of bolt installation	rpm	80–600
4	Torque of bolt installation	N m	0–200
5	Nut tightening torque	N m	0–750
6	Axial force of bolt	kN	0–610
7	Radial shear force of bolt	kN	0–1100
8	Bolt installation angle	°	0°–30°
9	Axial impact energy	kJ	0–11

applied torque was monitored by a sensor that was mounted to the sleeve and was used for applying torque to the nut.

Figure 2 shows the response of the rock bolts during and after installation with pretension. The resulting data are listed in Table 2. The torque versus time curves show that the torque on the rebar increased significantly with applied torque to the nut until a maximum was reached and then remained stable with time. For a high torque (e.g., 350 and 450 N m), a distinct decrease in the torque on the rebar was observed after installation. The rebar-to-nut torque ratio, which was indicated by the ratio of the torque on the rebar to the torque applied to the nut, was between 28 and 41%. A greater applied torque on the nut yielded a higher ratio, which indicates that the application of a larger torque on the nut may place the rock bolt into an unfavorable situation because of the high distortion by the rebar.

When the nut was tightened, the pretension that was applied to the rock bolt increased sharply as shown in the axial force versus time curves in Fig. 2b. A greater applied torque resulted in a greater pretension that was applied to the bolt. A torque of 100 N m generated a pretension of ~30 kN. A higher torque of 500 N m resulted in a pretension of 150 kN, which accounted for more than 60% of the yielding force of the bolt.

Figure 3 presents the test results of rock bolt that was installed inclined to the rock surface. The resulting data are listed in Table 3. The radial force of the rock bolt was measured using a force sensor at the borehole collar. Under this condition, the increase in the pretension was slower than that when the rock bolt was installed perpendicularly to the rock surface. With the same torque applied on the nut, the generated pretension on the inclined rock bolt was less than that on the perpendicular rock bolt. A greater applied torque yielded a greater difference in the generated pretension

Table 2 Values of pretension and torque obtained from rock bolt installed perpendicular to rock surface

Designed torque (N m)	Applied torque (N m)	Pretension (kN)	Torque on rebar (N m)	Rebar-to-nut torque ratio (%)
120	100	29.4	28	28
250	277	81.9	92	33
350	393	119.3	115	29
450	509	143.3	210	41

between the two cases. Theoretically, the tensile force F_e and the radial force F_r at the bolt end are related to the pretension F_p as follows:

$$\begin{aligned} F_p &= F_e \cos \theta, \\ F_r &= F_e \sin \theta, \end{aligned} \tag{1}$$

in which θ is the inclined angle.

For $F_e = 120$ kN, $\theta = 20^\circ$, the calculated $F_p = 112.8$ kN, and $F_r = 41.0$ kN.

The thread end of the rock bolt was subjected to a radial force at the borehole collar under the condition of inclined installation, see Fig. 3b. The radial force increased rapidly and then stabilized. A greater applied torque yielded a greater generated radial force by the thread end.

3.2 Response of Rock Bolts Subjected to Tension

After a rock bolt was pre-tensioned, an axial tensile load was applied to the rock bolt until failure occurred in terms of rebar breaking or anchor failure occurring. The loading rate was 0.3 kN/s. The mechanical behaviour of the rock bolt was evaluated by monitoring the axial force and torque on the rebar, and

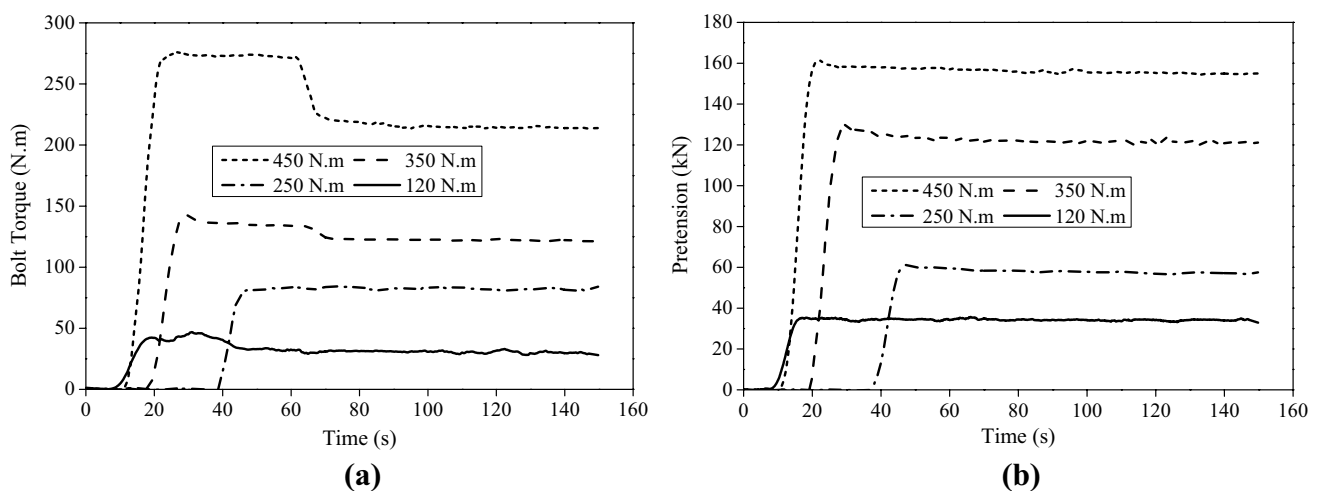


Fig. 2 Performance of rock bolt during and after installation with pretension. **a** The torque subjected on the rebar, **b** axial force subjected by the rebar

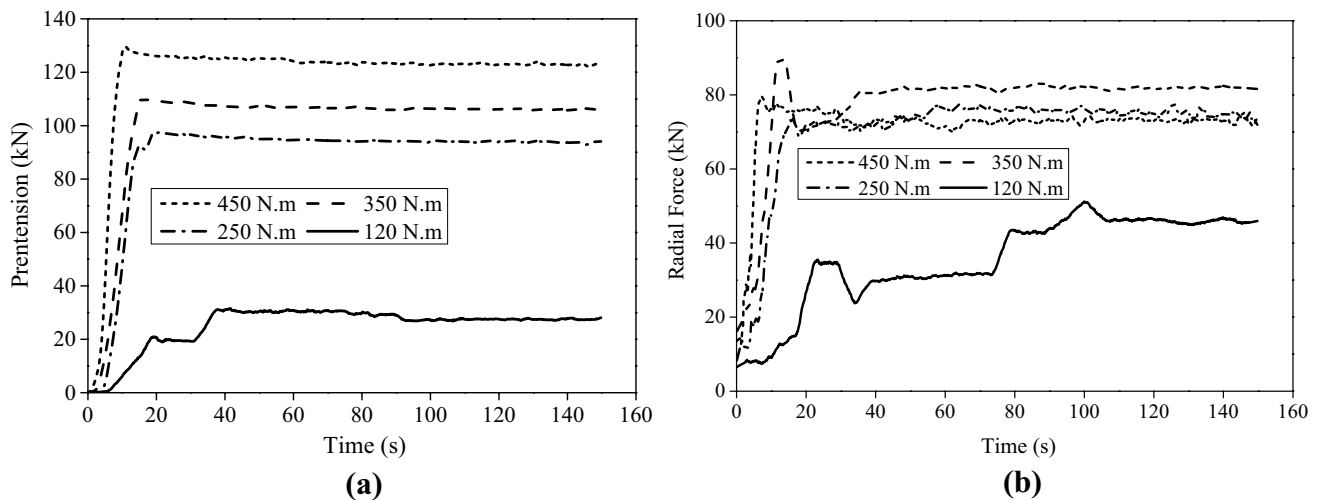


Fig. 3 Changes of pretension and radial force obtained from an experiment on rock bolt installed inclined to rock surface at 20°. **a** Pretension, **b** radial force

Table 3 Values of pretension and torque obtained from rock bolt installed inclined to rock surface

Installation angle (°)	Designed torque (N m)	Applied torque (N m)	Pretension (kN)	Torque on rebar (N m)	Rebar-to-nut torque ratio (%)	Radial force (kN)
10	120	124	25.3	17	14	51.3
20	120	134	22.0	27	20	42.8
20	250	262	67.8	77	29	79.4
20	350	382	100.4	129	34	63.0
20	450	518	121.4	203	39	84.0

the deformation of the rock bolt system. The deformation of the rock bolt system referred to the total axial deformation of the rock bolt and its accessories after the rock bolt was pretensioned, and the deformation during the pretension was not included.

Figure 4 shows the response of the rock bolts under pure tension after installation with pretension. The resulting data are listed in Table 4. The ultimate tensile force reached 89.7–93% of that of the rebar and 91.2–94.6% of that of the thread. The main reason for the decrease in tensile capacity was that the rebar was subjected to torque during the pretension, which did not place the rebar in pure tension but was a combination of tension and distortion. A greater applied torque for pretension yields a greater increase of composite stress. The composite stress σ_i can be calculated from

$$\sigma_i = \sqrt{\sigma_t^2 + 3\tau^2} \quad (2)$$

$$\tau_{\max} = 16 \frac{M_t}{\pi d^3} \quad (3)$$

where σ_t is the tensile stress, τ is the shear stress, M_t is the torque on rebar, and d is the rebar diameter.

For $\sigma_t = 300$ MPa, $M_t = 200$ N m, and $d = 22$ mm, the calculated $\sigma_i = 342.7$ kN, and the tensile stress was 87.5% of the composite stress.

The torque that was experienced by the rebar resulted from a decreased of pretension with axial displacement during the pulling process. The torque decreases occurred mainly in the elastic phase and the yielding stage before the strength hardening. The torque was released when the rebar started breaking.

Figure 5 shows the response of the inclined rock bolts under pure tension after installation with pretension. The installation angle appears to have a limited effect on the tensile capacity of the rebar. The installation angle trended to affect the rock bolt failure position. Vertical rock bolts broke at the thread section and inclined rock bolts broke at the rebar, most likely because, when a rock bolt was inclined to rock surface, the thread section was subjected to a combination of bending and tension, and the radial force caused tensile stress relief at the thread section. Under the same pretension, the inclined rock bolts was slightly larger than

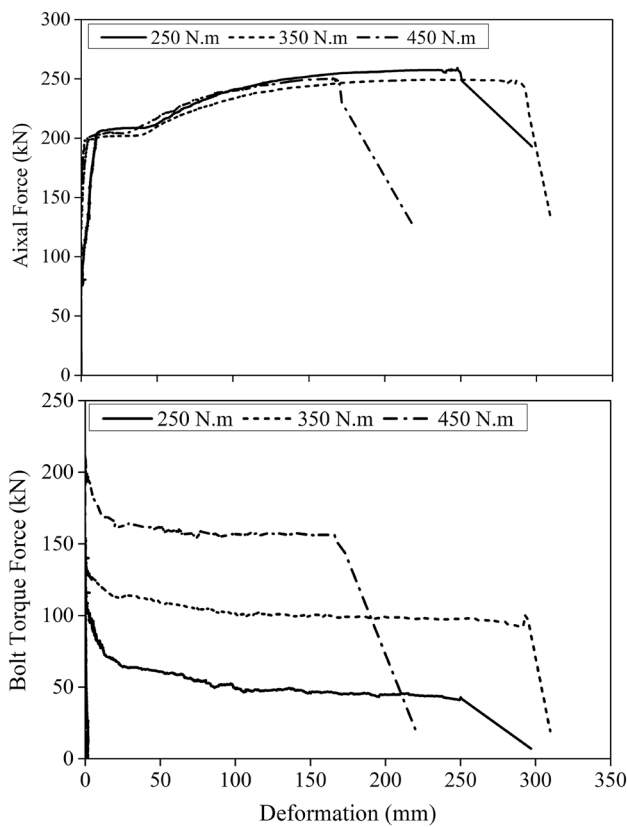


Fig. 4 Response of rock bolts under pure pull-out tests after installation with different torque applied on the nut to produce pretension. The rock bolts were installed perpendicular to rock surface

that of the vertical rock bolts because the inclined rock bolt elongation broke at the rebar section, which had a greater deformability than the thread section.

3.3 Response of Rock Bolts Subjected to Shear Loading

Shear tests were performed to assess the mechanical response of a rock bolt under shear loading. The rock bolt

was installed either perpendicular or inclined to rock surface. A torque of either 250 N·m or 350 N·m was applied to the nut to produce a pretension during installation. A rock bolt may have suffered tension before shear tests. To assess the response of the rock bolt under this condition, two inclined rock bolts were pulled with an axial force of 170 kN before the shear tests. The shear load was applied with a loading rate of 0.3 kN/s until the rock bolt broke.

Figure 6 shows the response of two perpendicular rock bolts under shear loading. The shear force increased with shear displacement. At the initial stage of the shear test, the shear force increased slightly with shear displacement, which was attributed to the joint gap. The maximum shear force can reach up to 80% of the ultimate tensile capacity of the rock bolt. The axial force of the rock bolt maintained the pre-tensioned value at the initial stage of the shear test. When the shear displacement exceeded 20 mm, the axial force began to increase with shear displacement until failure. The maximum axial force was ~ 2/3 of the ultimate tensile capacity of the rock bolt.

Figure 7 shows the response of four inclined rock bolts under shear loading. For the inclined rock bolts without pulling before shear, the maximum shear displacement and shear force were like the values from shear tests on rock bolts that were installed perpendicular to rock surface. When the rock bolts were pulled with an axial force of 170 kN, the maximum shear force decreased significantly, which indicates that a higher axial load that is experienced by a rock bolt yields a lower rock bolt shear resistance. The axial behavior of the inclined rock bolts showed a similar behavior to the perpendicular rock bolts in shear tests under pre-tension and no pulling before the shear test. With pulling before the shear test, the axial load of the rock bolt tended to be stable throughout the shear test process. The axial deformation reached ~ 5–10 mm. During the shear process, the rebar experienced a combined force of bending, tension, and shear because of the joint gap. The bolt failed with a pattern of combined bending and shearing as shown in Fig. 8.

Table 4 Result of pull-out tests on rock bolt installed with pretension

Installation angle (°)	Torque on nut (N m)		Axial force (kN)			Elongation at maximum axial force (%) Rock bolt system
	Designed	Applied	Pretension	Yield	Maximum	
0	250	296.9	80.9	208.3	259.7	12.6
0	350	399.9	108.2	203.5	251.0	12.3
0	450	508.9	143.3	206.1	250.3	10.9
20	250	283.4	80.3	204.1	258.0	13.4
20	350	401.4	109.7	202.3	254.2	13.5
20	450	543.0	149.3	202.2	251.1	12.0

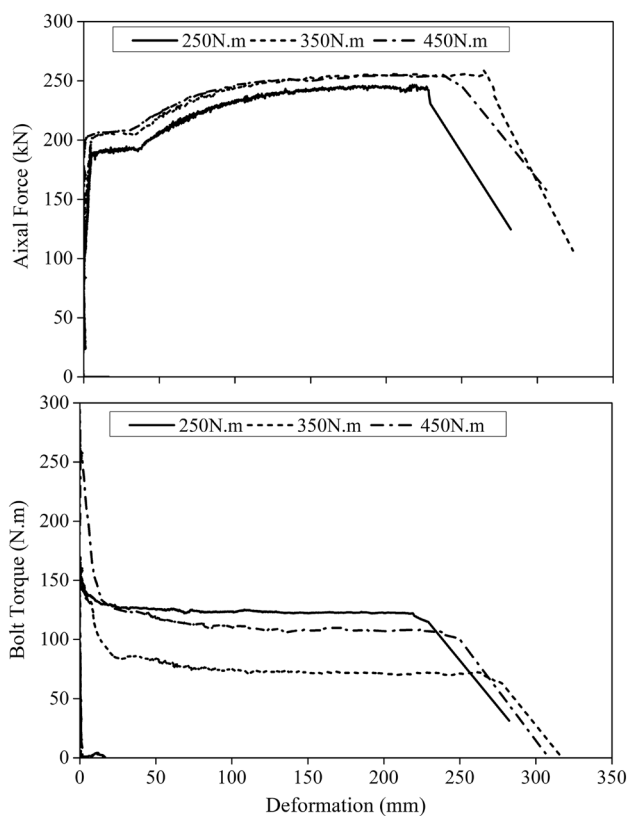


Fig. 5 Response of rock bolts under pure pull-out tests after installation with different torque applied on the nut to produce pretension. The rock bolts were installed inclined to rock surface

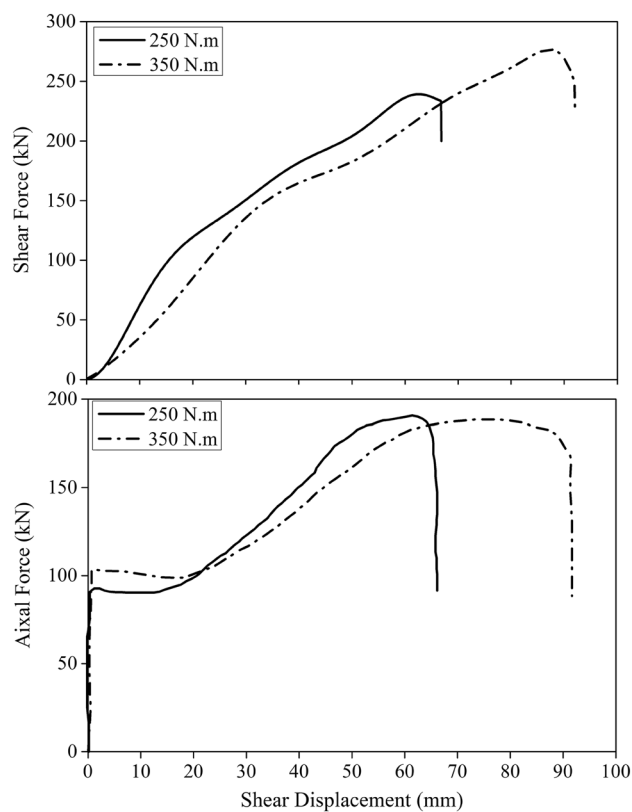


Fig. 6 Shear behavior of rock bolts installed with different torques applied on the nut to produce pretension. The rock bolts were installed perpendicular to rock surface

3.4 Response of Pre-tensioned Rock Bolts Under Dynamic Impact

Impact tests were performed to evaluate the response of a rock bolt under dynamic impact conditions. During these tests, a single impact was applied directly to a pre-tensioned rock bolt and the pull-out test was performed until the rock bolt broke or the anchor failed. Two different pretensions (100 N·m and 250 N·m) and two different impact energies (5 kJ and 10 kJ) were considered in these tests. During the processing of pendulum hitting the beam, repeated shocks and a state of oscillation occurred in a very short time. The pendulum rebounded backward at a certain small angle (see Fig. 9). A higher the impact energy yielded a larger rebound angle. Pretension appears to have a limited influence on the rebound angle. Distinct changes in torque and pretension of the rock bolts were observed during the impact (see Fig. 10). The torque and pretension remained stable at the beginning of the impact, and then decreased significantly to zero after a certain period, which suggests that the bolt was unloaded completely after impact.

Figure 11 shows the changes in dynamic load with time during impact loading. Under a 10 kJ of impact load, the

peak axial dynamic load of the rock bolt was 400 kN, which exceeded the static limit of the tensile load of the rebar material by more than 40%. The duration of the dynamic load was 90–180 ms. A limited difference was observed in the peak value of the dynamic load that was caused by impact at 5 and 10 kJ, but the higher 10 kJ energy impact generated a longer loading period on the rock bolt. Figure 12 shows the changes in the axial displacement of the rock bolt during impact loading. Under a 10 kJ of impact load, the maximum displacement of the rock bolt system reached 25 mm. The anchoring end slipped instantaneously and rebounded under the impact. With oscillating effects, the impact beam position reciprocated along the axial direction. After the impact, partial plastic deformation formed on the rock bolts. When a lower impact energy of 5 kJ was applied, the maximum displacements of the rock bolt system were ~40% of that caused by the 10 kJ impact energy. Rock bolt deformation that was induced by impact with different amounts of pretension was close, which suggests that pretension has a limited effect on dynamic-load-bearing capacity.

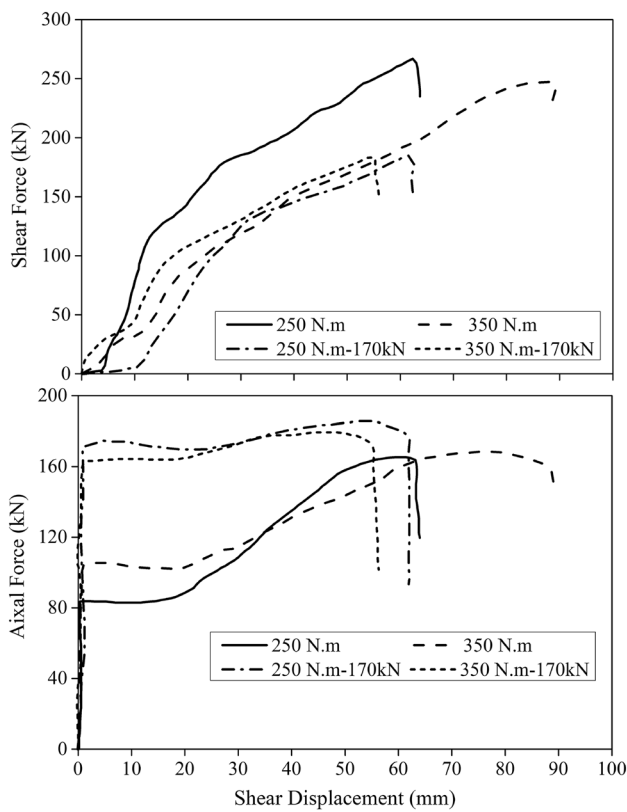


Fig. 7 Shear behavior of rock bolts installed with different torques applied on the nut to produce pretension. The four rock bolts were installed inclined to rock surface at 20°. Two of them were pulled to 170 kN before the shear test



Fig. 8 Failure pattern of rock bolt subjected to shear load

4 Discussion

Pre-tension plays a key role in improving the active support of a rock bolt system and controlling surrounding rock deformation (Stankus and Peng 1996; Frith and Thomas 1998; Peng 1998). Pre-tension is normally applied by

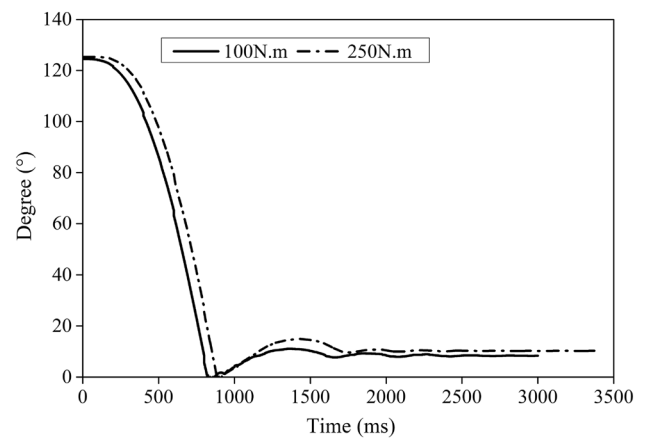


Fig. 9 Changes of angle of the pendulum during impact test

tightening the nut, which applies a certain torque to the rebar. The pretension that is applied on the rebar depends on the torque that is applied on the nut, and on the friction between the nut and the washer, the rebar diameter, and the angle at which the bolt is installed (Kang et al. 2016). Figure 3 and Table 2 show that as the applied torque increases, the torque, tensile force, and bending stress that are subjected by the bolt increase. The relationship between the torque that is applied on the nut and the pretension by the rebar is not linear. The rebar elongation decreased substantially under a high pretension. When the rock bolt was pre-tensioned by applying a torque of 300–400 N·m, the elongation at a maximum axial force was 94–96% of that of the rebar. When the applied torque was 500 N·m, the elongation dropped to 83% of that for the rebar. Two reasons for this phenomenon include (1) the fact that the bolt consumed part of the deformability during pretension, and (2) the rebar was subjected to a combination of tension and distortion, rather than pure tension, which lead to the decrease in deformability and tensile strength of the rock bolt. To the best of our knowledge, this finding has not been reported by other researchers. Pull-out tests have been used extensively to evaluate the mechanical behavior of rock bolts that are anchored by resin or grout (Kılıc et al. 2002, 2003; Li 2012; Thenevin et al. 2017). In traditional pull-out tests, a rock bolt is free-of-load and is not subjected to torque and pretension before pulling out. This is generally no the case in the field. Thus, it is suggested that the traditional pull-out test results represent the upper bound values of the capacity of the rock bolt.

In tunneling and mining practice, deformations of the rock mass that surround an opening tend to have already occurred before rockbursts. Therefore, a rock bolt has experienced complex loads, including bending and twisting during installation, tensile stress because of rock mass

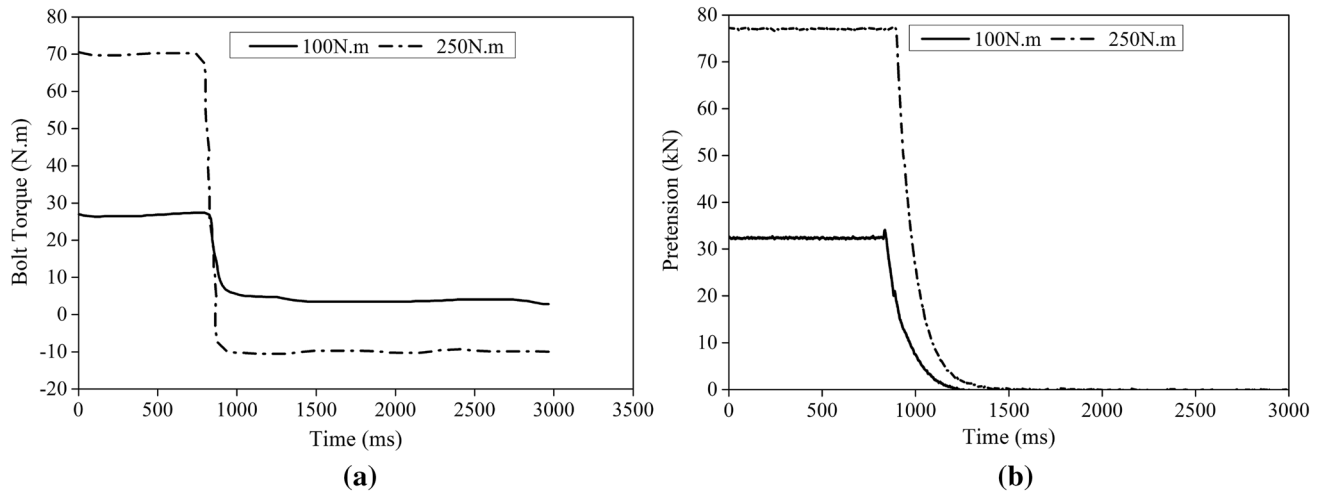


Fig. 10 Response of the bolt during impact test. **a** Torque, **b** pretension

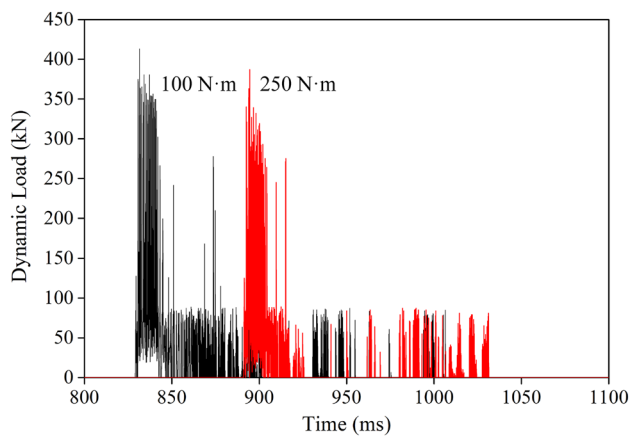


Fig. 11 Changes of dynamic load suffered by the bearing plate during impact test

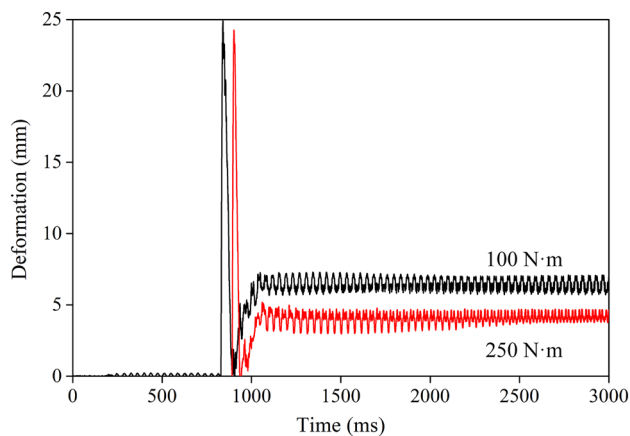


Fig. 12 Changes of deformation of the rock bolt system during impact test

expansion, and shearing because of rock joint sliding. Most dynamic impact equipment, however, tests the response of rock bolts that are load-free before the dynamic load. The developed equipment allows for impact tests on rock bolts that are subjected to complex loads. Using this equipment, impact tests were performed on 16 rock bolts that were subjected to a tensile load. No rock bolt failed after the impact because of the relatively low impact energy of 10 kJ. Pull-out tests were conducted until the rock bolt was pulled to break or pulled out from the concrete column. For rock bolts that were subjected to a relatively small tension before impact, only limited displacement occurred during impact, the peak value of axial dynamic load was close to the pretension of the rock bolt. For rock bolts that were subjected to a relatively high tension (i.e., 210 kN), the impact load caused a dramatic decrease in the anchoring capacity of the rock bolt that was characterized by a remarkable displacement (60 mm) in the anchoring end and a sharp drop in the axial force. The torque dropped to zero after impact, but the rebar still bore a certain tensile load with a value close to the tensile load that was applied before the impact. A higher tension prior to impact led to a larger amount of rock bolt deformation after impact. For rock bolts that were subjected to a high tension before impact, sliding along the entire anchored section of the rock bolt was observed when the rock bolts were pulled out after impact. This behavior suggests that a dynamic load may cause the failure of the bonding section of resin-anchored rock bolts, which lead to failure of the rock bolt support without any rebar breaks. This phenomenon is observed frequently in the field where rockbursts cause failure of rock bolt-anchored rock mass (Wu et al. 2019).

For all the tested rock bolts, the obtained ultimate tensile capacity was ~90% of the rebar material, and the elongation

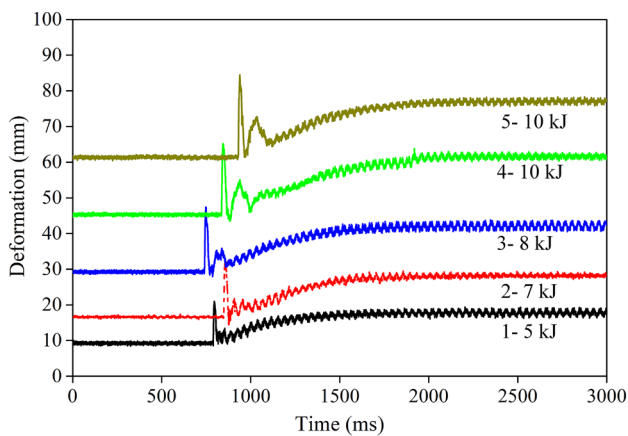


Fig. 13 Changes of bolt deformation during multiple impacts. The first number in the legend indicates the sequence of the multiple impacts and the second number indicates the applied energy of the impact

was 77–86% of the rebar, which suggests that the impact load had a significant effect on the deformability of the rock bolt. This finding suggests that the capacity, especially the deformation capacity of a rock bolt may decrease significantly after successive containment of the deformation of the surrounding rock mass that results from rockbursts. Therefore, the rock bolt may fail in future rockbursts or under severe deformation. To evaluate the behavior of a rock bolt under multiple dynamic loading cycles, multiple impact tests were performed. The rock bolt was pulled to a certain level (i.e., 240 kN) after pretension. Multiple impacts (i.e. five impacts with energies of 5, 7, 8, 10 and 10 kJ in sequence) were conducted. After each impact, the bolt was pulled to the pre-impact load level. The pull-out test was conducted after multiple impacts until the rock bolt broke. Figure 13 shows the response of the rock bolt under multiple impacts. At each time of the impact, an irreversible plastic deformation formed on the rock bolts. This finding is consistent with the results of Li and Doucet (2012) who performed multiple impact tests on a D-bolt using drop weight test equipment.

5 Conclusions

The developed test equipment provides a useful tool to evaluate the mechanical behavior of rock bolt under realistic loading conditions, which is a combination of complex loadings, including pretension, tensioning, torsion, bending, shearing, and impact. New findings were obtained on the mechanical response of rock bolts that cannot be evaluated using traditional pull-out, shear, and impact test. By applying a high torque to the nut for pretension, a rock bolt may place the rock bolt in an unfavourable situation because of the high distortion by the rebar, that is, a large decrease

(i.e., 77–86%) in tensile strength and elongation. The maximum shear force of a rock bolt can reach 80% of its tensile capacity. Rock bolt tensioning before shear can decrease the shear resistance capacity further. An impact load can exert a significant influence on the remnant capacity of the rock bolt if it has not broken after impact. Influences include the occurrence of irreversible plastic deformation, which is an approximately 10% decrease in the ultimate tensile capacity, and a significant decrease in the elongation. The capacity, especially the deformation capacity of a rock bolt, may decrease significantly after successive containment of the deformation of the surrounding rock mass that results from rockbursts.

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Compliance with Ethical Standards

Conflict of interest The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

- Björnfot F, Stephansson O (1984) Interaction of grouted rock bolts and hard rock masses at variable loading in a test drift of the Kiirunavaara Mine, Sweden. *Balkema, Rotterdam*, pp 377–395
- Dunnam RK (1976) Anchorage tests on strain gauged resin bonded bolts. *Tunn Tunn Int* 8:73–76
- Farmer IW (1975) Stress distribution along a resin grouted rock anchor. *Int J Rock Mech Min Sci Geomech Abstr* 12:347–351. [https://doi.org/10.1016/0148-9062\(75\)90168-0](https://doi.org/10.1016/0148-9062(75)90168-0)
- Ferrero AM (1995) The shear strength of reinforced rock joints. *Int J Rock Mech Min Sci Geomech Abstr* 32:595–605. [https://doi.org/10.1016/0148-9062\(95\)00002-X](https://doi.org/10.1016/0148-9062(95)00002-X)
- Freeman T (1978) The behaviour of fully-bonded rock bolts in the kielder experimental tunnel. *Tunn Tunn Int* 10:37–40
- Frith R, Thomas R (1998) The pre-tensioning pedigree. *Aust Min Mon Undergr Equip Technol* 7:68–72
- Gaudreau D (2004) Performance assessment of tendon support systems submitted to dynamic loading. *École Polytechnique de Montreal, Montreal*
- Grasselli G (2005) 3D Behaviour of bolted rock joints: experimental and numerical study. *Int J Rock Mech Min Sci* 42:13–24. <https://doi.org/10.1016/j.ijrmms.2004.06.003>
- Jalalifar H, Aziz N, Hadi M (2006) The effect of surface profile, rock strength and pretension load on bending behaviour of fully grouted bolts. *Geotech Geol Eng* 24:1203–1227. <https://doi.org/10.1007/s10706-005-1340-6>
- Kang H, Lin J, Wu Y (2009) Development of high pretensioned and intensive supporting system and its application in coal mine roadways. *Proc Earth Planet Sci* 1:479–485. <https://doi.org/10.1016/j.proeps.2009.09.076>
- Kang H, Wu Y, Gao F et al (2013) Fracture characteristics in rock bolts in underground coal mine roadways. *Int J Rock Mech Min Sci* 62:105–112. <https://doi.org/10.1016/j.ijrmms.2013.04.006>

- Kang H, Wu Y, Gao F et al (2016) Mechanical performances and stress states of rock bolts under varying loading conditions. *Tunn Undergr Space Technol* 52:138–146. <https://doi.org/10.1016/j.tust.2015.12.005>
- Kang H, Yang J, Meng X (2015) Tests and analysis of mechanical behaviours of rock bolt components for China's coal mine roadways. *J Rock Mech Geotech Eng* 7:14–26. <https://doi.org/10.1016/j.jrmge.2014.12.002>
- Karanam UMR, Dasyapu SK (2005) Experimental and numerical investigations of stresses in a fully grouted rock bolts. *Geotech Geol Eng* 23:297–308. <https://doi.org/10.1007/s10706-004-9518-x>
- Kılıc A, Yasar E, Atis CD (2003) Effect of bar shape on the pull-out capacity of fully-grouted rockbolts. *Tunn Undergr Space Technol* 18:1–6. [https://doi.org/10.1016/S0886-7798\(02\)00077-9](https://doi.org/10.1016/S0886-7798(02)00077-9)
- Kılıc A, Yasar E, Celik AG (2002) Effect of grout properties on the pull-out load capacity of fully grouted rock bolt. *Tunn Undergr Space Technol* 17:355–362. [https://doi.org/10.1016/S0886-7798\(02\)00038-X](https://doi.org/10.1016/S0886-7798(02)00038-X)
- Li CC (2012) Performance of D-bolts under static loading. *Rock Mech Rock Eng* 45:183–192. <https://doi.org/10.1007/s00603-011-0198-6>
- Li CC (2010) Field observations of rock bolts in high stress rock masses. *Rock Mech Rock Eng* 43:491–496. <https://doi.org/10.1007/s00603-009-0067-8>
- Li CC, Doucet C (2012) Performance of D-bolts under dynamic loading. *Rock Mech Rock Eng* 45:193–204. <https://doi.org/10.1007/s00603-011-0202-1>
- Ortlepp WD, Stacey TR (1998) Performance of tunnel support under large deformation static and dynamic loading. *Tunn Undergr Sp Technol* 13:15–21. [https://doi.org/10.1016/S0886-7798\(98\)00022-4](https://doi.org/10.1016/S0886-7798(98)00022-4)
- Pellet DF, Egger P (1996) Analytical model for the mechanical behaviour of bolted rock joints subjected to shearing. *Rock Mech Rock Eng* 29:73–97. <https://doi.org/10.1007/BF01079755>
- Peng S (1998) Roof bolting adds stability to weak strata. *Coal Age Mag* 11:32–38
- Player JR (2012) Dynamic testing of rock reinforcement systems. PhD Thesis, Western Australian School of Mines, Curtin University of Technology
- Player JR, Villaescusa E, Thompson AG (2004) Dynamic testing of rock reinforcement using the momentum transfer concept. In: *Proceedings of the 5th Int. Symp. Rock Support and Reinforcement*, p 29
- Spang K, Egger P (1990) Action of fully-grouted bolts in jointed rock and factors of influence. *Rock Mech Rock Eng* 23:201–229. <https://doi.org/10.1007/BF01022954>
- Stankus J, Peng S (1996) A new concept for roof support. *Coal Age Mag* 9:2–6
- St-Pierre L, Hassani FP, Ouellet J, Radziszewski PH (2007) An investigation on the dynamic testing, properties and responses of support systems. In: *Proceedings of the 11th ISRM congress. International society for rock mechanics and rock engineering, Lisbon, Portugal*, p Paper-039
- St-Pierre L, Hassani FP, Radziszewski PH, Ouellet J (2009) Development of a dynamic model for a cone bolt. *Int J Rock Mech Min Sci* 46:107–114. <https://doi.org/10.1016/j.ijrmms.2008.05.005>
- Thenevin I, Blanco-Martín L, Hadj-Hassen F et al (2017) Laboratory pull-out tests on fully grouted rock bolts and cable bolts: results and lessons learned. *J Rock Mech Geotech Eng* 9:843–855. <https://doi.org/10.1016/j.jrmge.2017.04.005>
- Wu Y, Gao F, Chen J, He J (2019) Experimental study on the performance of rock bolts in coal burst-prone mines. *Rock Mech Rock Eng* 52:3959–3970. <https://doi.org/10.1007/s00603-019-01794-9>
- Yi X, Kaiser PK (1994) Impact testing for rockbolt design in rockburst conditions. *Int J Rock Mech Min Sci Geomech Abstr* 31:671–685. [https://doi.org/10.1016/0148-9062\(94\)90007-8](https://doi.org/10.1016/0148-9062(94)90007-8)

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