Preprint 19-054

LOADING CHARACTERISTICS OF MECHANICAL RIB BOLTS

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ABSTRACT

A conventional mechanical anchor bolt consists of a smooth bar threaded at the anchor end, with a conical wedge, and a mechanical shell anchor. When the smooth bar is torqued, the conical wedge pushes the shell anchor against the borehole wall. Coal mines use mechanical bolts in addition to other types of bolts to control the deformation and stabilize the yielded coal ribs. Limited research has been conducted to understand how a mechanical anchor performs in a coal rib. Researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted the study described in this paper to define the loading characteristics of mechanical bolts (stiffness and capacity) installed in coal ribs at five underground coal mines.

Standard pull-out tests were performed in this study to define the loading characteristics of a mechanical rib bolt. Based on the strength of the coal seam and the conditions of the coal mines, the bolts were installed at different amounts of torque. A typical tri-linear load-deformation response was obtained from these tests. It was found that the anchorage capacity depends on the coal strength, and the anchorage stiffness depends on the installation torque. The outcome of this research provides essential data for rib support design.

INTRODUCTION

Rib falls are a serious hazard in underground coal mines. In the last 10 years, rib failures have resulted in 17 fatalities, representing 52% of the ground-fall fatalities in underground coal mines in the United States (MSHA, 2018). Although resin bolts has been used increasingly in the last few years to control coal ribs, mechanical bolting (mainly expansion-shell bolts) is still used in many underground coal mines. Recently, NIOSH researchers surveyed 90 sites in 14 underground coal mines in the Eastern United States and found that 79% of the mines determine their rib support requirement based on the depth, mining height, and the loading conditions, of which 35% use the conventional mechanical bolts. Conventional mechanical bolts are preferable for rib support because they do not require the miners to be too close to the rib during rib bolting. Hence, using the conventional mechanical rib bolts can reduce the risk of injuries and fatalities during the installation process.

The mechanical bolt or the point-anchored bolt is the oldest type of rock bolt that is still in use today. The point-anchored bolt is a tensioned bolt anchored down the hole with a mechanical expansion shell or a grouted medium (Peng and Tang, 1984). Figure 1 shows the components of the mechanical anchor bolt.

The mechanical anchor bolt consists of a plug, a shell anchor, a headed smooth bar with the top end threaded, a bearing plate, a hardened washer, and sometimes a friction-reducing washer. The shell anchor can be either standard or bail type. The shell of the standard type is held in place by a nut, while the bail anchor uses a strap to hold the shell in place (Peng, 2008). The diameter of the smooth bar is generally 5/8 in for the #5 bolt or 6/8 in for the #6 bolt. The diameter of the hole that the bolt is inserted into must be carefully controlled since an oversized hole can result in poor anchorage (Moss, 1971). The anchorage is obtained by applying torque to the bolt head, which in turn pulls the wedge down in the shell and expands the serrated leaves against the sides of the hole-wall. In the resin-grouted anchor, the resin replaces the mechanical expansion shell at the end of the hole. The anchorage is achieved by bonding between the resin, bolt, and the hole-wall.

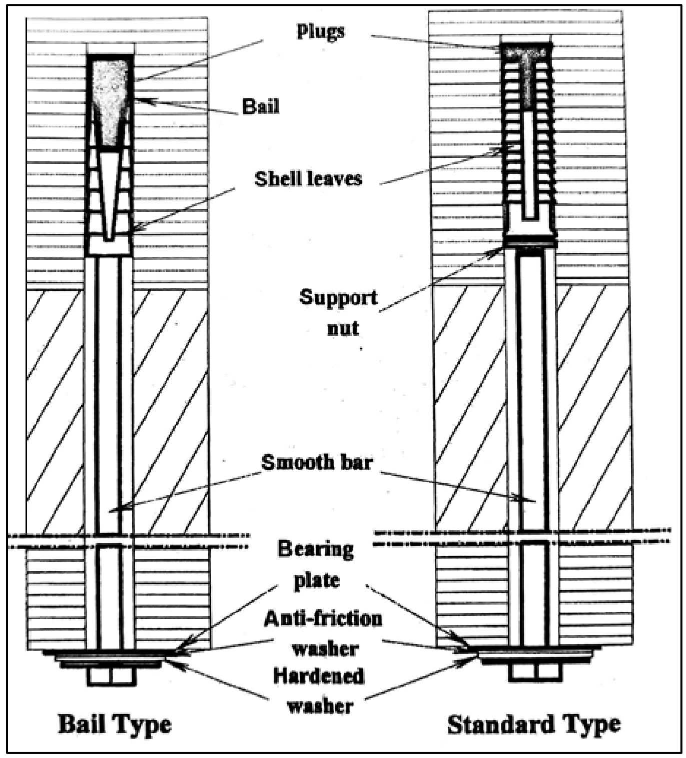


Figure 1. Mechanical bolts (Peng, 2008).

The design of rib bolting in U.S. coal mines is based on a trial-and-error process, which is insufficient to eliminate injuries and fatalities caused by rib falls. Therefore, NIOSH researchers are developing an engineering design procedure for rib support. Rib support design requires clear understanding of the behavior of mechanical anchors in coal ribs. Anchorage capacity and the shear stiffness are the key parameters that govern the behavior of mechanical bolts. Standard pull-out tests can be used to determine the anchorage capacity and the shear stiffness of the anchorage. The anchorage capacity is defined as the load at which an excessive anchorage slippage or yielding of the bolt occurs. Howe (1968) analyzed the factors affecting the anchorage performance of the expansion shell and found that the anchorage capacity increases with increasing the wedge angle and the bearing area of the leaves.

Limited research has been conducted to understand how a mechanical anchor performs in a coal rib. Tadolini (1985) conducted 37 pull-out tests on bolts in a coal roof. Standard roof support practices are not directly applicable to ribs (Hebblewhite, 2006). Hence, the conclusion drawn by Tadolini (1985) cannot apply to ribs. Roof bolts are used to create a thick, strong beam by unified thin roof layers or by suspending the immediate roof in a strong roof stratum. On the other hand, rib bolts are used to contain yielded ribs in place and control rib deformation.

Larson and Dunford (1996) conducted 220 pull-out tests for expansion-shell mechanical rib bolts in two coal seams of two different mines. Larson and Dunford found that the anchorage system exhibit bilinear response during the pull-out test, and the condition, e.g. age and coal strength, of the rib is the most significant factor in determining mechanical anchorage capacity. It follows that if the anchorage is located within the yield zone, the anchorage capacity will be reduced. However, Larson and Dunford did not provide an acceptable explanation for the bilinear model they found from the test results.

This paper studies the behavior of mechanical expansion anchor bolts in coal pillar ribs and provides a detailed explanation of the main parameters required to obtain a successful rib support design. Factors affecting the anchorage capacity and the stiffness of the mechanical bolts are explored, and a torque-tension model based on the best fit for experimental pull-out test results is introduced. The outcome of this research improves understanding of how a mechanical anchor performs in a coal rib and provides essential data for rib support design.

TORQUE-TENSION RELATIONSHIP OF MECHANICAL BOLTS

During the installation of mechanical bolts, an installation torque is applied on the head of the bolt. The range of installation torque is recommended by the bolt manufacturer. The applied torque is converted into uniform tension in the smooth bar between the shell at the end of the bolt and the bearing plate set against the rib. To maximize the torque-tension conversion, a friction-reducing washer is placed between the bearing plate and the bolt head. The applied tension is activated immediately to build the compression zone in the supported rib along the bolt length. The relationship between the applied torque and the induced tension is called the torque-tension ratio. The torque-tension ratio is highly affected by the mechanical details of the bolt/anchor/bearing plate assembly (Peng, 2008).

The torque-tension ratio of the tested mechanical bolts in a coal pillar rib was determined experimentally by NIOSH researchers. Six (6) bail-type mechanical bolts of 5/8-in diameter and 4-ft long were installed in the coal seam of the NIOSH Safety Research Coal Mine, Pittsburgh, PA. The installation torque was applied manually using a calibrated torque wrench as shown in Figure 2. An assembly of pull collar, friction-reducing washer, and load cell was placed between the bolt head and the bearing plate. The pull collar was included in the bolt assembly to replicate the pull-out test assembly conducted in the study as seen in Figure 2. The torque wrench was used to measure the applied torque, and the load cell was used to measure the induced tension in the bolt. The relationship between the applied torque and the induced tension in the tested bolts is non-linear as shown in Figure 3.

Figure 2. Applying the installation torque.

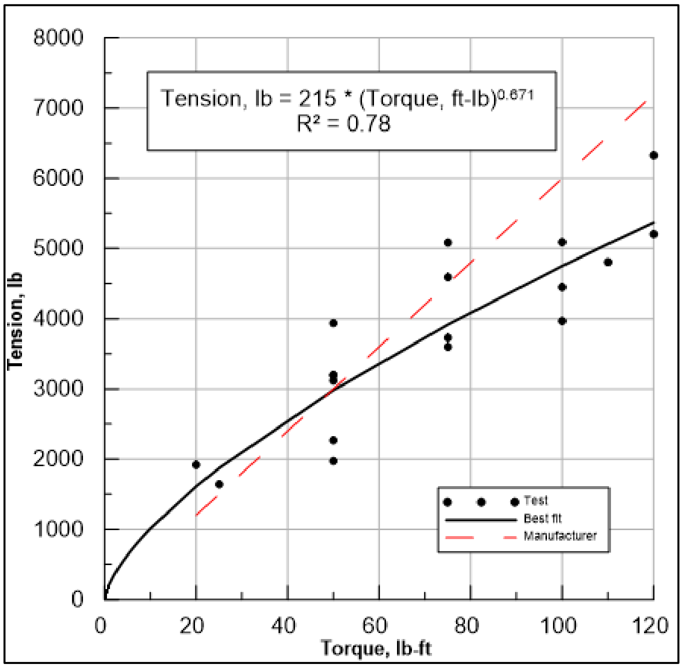


Figure 3. Torque-tension relationship of the tested bolt.

The scatter of test points is explained by the inhomogeneity of the coal. The best fit for the torque-tension relationship of the 5/8-in-diameter mechanical bolt is given by the following non-linear model equation:

$$P = 215 \times T^{0.671} \qquad \text{(Equation 1)}$$

where,

P is the bolt tension (lbs) and
T is the bolt installation torque (ft-lb).

The recommended torque-tension ratio is 50-lb tension per foot bound of torque for bolts without hardened washers or 60-lb tension per foot of torque with hardened washer. Therefore, the torque-tension relationship provided by the manufacturer of the tested mechanical bolt (dashed line in Figure 3) is given by the following linear model equation:

$$P = 60 \times T \qquad \text{(Equation 2)}$$

The induced tensions in the tested bolts at a torque greater than 75 ft-lb were smaller than those calculated by the manufacturer's formula (Equation 2). The reduction in the torque-tension ratio could be explained by the following: (1) loss of friction between the pull collar and other parts, and/or (2) coal yielding at anchor-end because of induced high radial stresses and relatively low coal strength of 2,252 psi. In the future, the torque-tension relationship will be obtained for stronger coal.

PULL-OUT TEST MECHANISM OF MECHANICAL BOLTS

The standard roof bolt anchorage testing procedure was followed to conduct the pull-out tests for mechanical bolts installed in coal ribs (AMC Coal Division Committee on Roof Action, 1959). A standard pull gear was used to determine the load-displacement curves of the tested bolts. Figure 4 shows a schematic drawing of the components of the standard pull gear. A load cell (part 21) and a ¼-in plate (part 20) are added to the standard pull gear to directly measure the induced bolt load.

A pull-out test was conducted for the bail-type mechanical bolt of 5/8-in diameter and 4-ft long installed in the NIOSH Safety Research Mine's coal seam in Pittsburgh, PA. The NIOSH research mine is an old room-and-pillar mine that was mined in the Pittsburgh coal seam. The bolt was manually torqued to 50 ft-lb using a calibrated torque wrench. Figure 5 shows the pull gear mounted on the pre-tensioned rib bolt before testing. It shows the loading cell sandwiched between two loading plates. The load applied on the bolt is recorded simultaneously by the load cell (part 21, Figure 4) and the pressure transducer connected to the hydraulic jack (part 2, Figure 4).

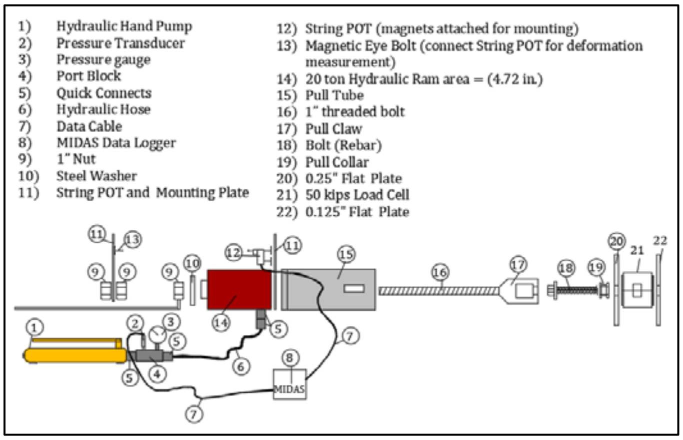


Figure 4. Pull-out test gear components.

Figure 5. Pull-out test gear mounted on the tested bolt.

Figure 6 shows the recorded load-displacement curves of the tested rib bolt. The bolt load recorded by the load cell is illustrated by dashed lines, and the jack load recorded by the pressure transducer is illustrated by a solid line.

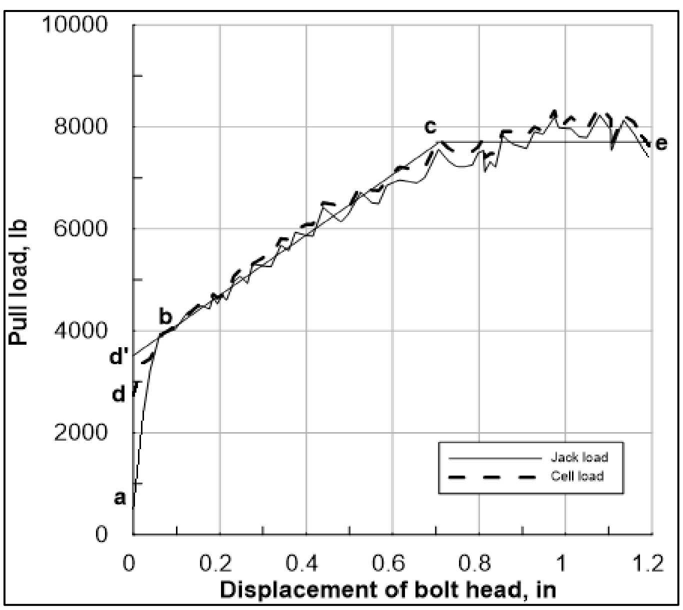


Figure 6. Load-displacement curves.

The cell load-displacement curve yields the actual bolt loading and bolt/coal interaction during the pull-out test. Generally, the standard pull gear does not include the load cell. Hence, the jack load-displacement curve (Figure 6) is a typical load-displacement behavior for standard pull-out tests. Three distinct portions may be identified in the jack load-displacement curve. The jack load-displacement response can be simplified by tri-linear curves (Line a-b, Line b-c and Line c-e, Figure 6):

(1) The first portion (Line a-b) is between the initial application of jack load (Point a) and the point at which the jack load and the cell load become equal (Point b). At Point a, the jack load begins to transfer to the bolt. Up until Point a, slack is being taken out of the test equipment. Line a-b has no significance for the anchorage mechanism of the mechanical bolt other than to indicate the point at which the jack load and the cell load became equal (Point b) (AMC Coal Division Committee on Roof Action, 1959).

(2) The center portion (Line b-c) where the jack load and the cell load coincide and increase linearly. The slope of Line b-c is a measure of the shear stiffness of the shell/coal anchorage. The shear stiffness of the mechanical anchorage is calculated as 6,000 lbs/in. The standard roof bolt anchorage testing procedure (AMC Coal Division Committee on Roof Action, 1959) proposed that the intercept (Point d') of the center portion (Line b-c) is a good approximation for the pre-tension load. The approximated pre-tension load was found to be 3,560 lbs., while the actual pre-tension load (Point d) measured by the load cell was 2,740 lbs. The suggested approximation of the pre-tension load overestimates the actual pre-tension load by about 30%.

(3) The flat portion (Line c-e) where the anchorage capacity is reached, the anchor slips when applying more load. The measured anchorage capacity of the tested bolt ranges from 7,900 to 8,100 lbs. At Point b, the calculated shear stresses induced at the borehole wall became greater than or equal to the in-situ shear strength of coal. The ultimate shear stress (τ) at the shell/coal interface is approximated by the following equation:

$$\tau = \frac{T}{f \times \pi \times D \times L} \qquad \text{(Equation 3)}$$

where

T is the anchorage capacity (T=7,900–8,100 lbs.),
D is the diameter of the shell/hole (D = 1-3/8 inch),
L is the length of the shell (L = 2 inch), and
f is the shell/coal contact factor which represents the effective surface area of shell leaf (f = 0.56).

Hence, the ultimate shear stress of the tested bolt ranges from 1,633 psi to 1,674 psi. The associated radial stress (σ_r) at the shell/coal interface is approximated by the following equation (Thompson and Villaescusa, 2013):

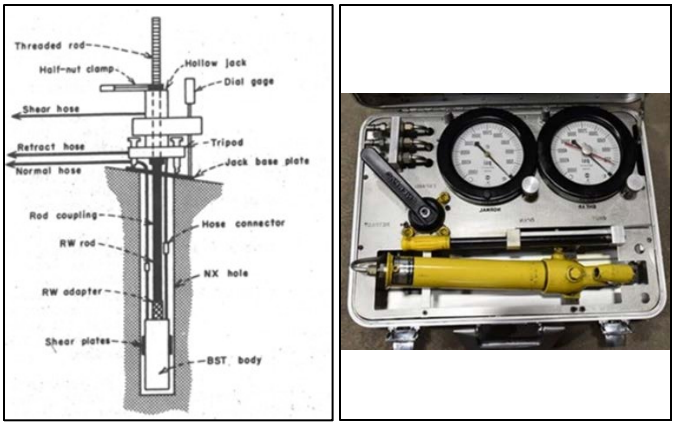
$$\sigma_r = \frac{\tau}{\tan(\alpha + \varphi_b)} \qquad \text{(Equation 4)}$$

where

α is the taper angle of the cone/leaf interface ($\alpha = 14^o$), and
φ_b is the friction angle at the cone/leaf interface ($\varphi_b = 8.5^o$).

Hence, the ultimate radial stress of the tested bolt ranges from 3,942 psi to 4,042 psi.

Borehole shear tests (BST) were conducted at the test site to validate the anchorage mechanism of the mechanical bolt. The BST is a device for measuring the Mohr-Coulomb in-situ strength parameters of coal material using a 3-inch borehole drilled at the test site. The BST was developed in 1976 by the Bureau of Mines (Haramy, 1981). Figure 7 shows the main components of the BST—the shear head and the console. The shear head has two shear plates which are mounted at the end of a double-acting hydraulic cylinder. The plates are fixed in place and linked to individual push plates, which apply the normal force. The main components of the console are the hand pump, the normal and shear gages, and the pump valve for switching between normal and shear modes.



(a) Shear head (Haramy, 1981). (b) Console

Figure 7. Main components of the BST.

The BST assembly and test procedure suggested by the Bureau of Mines was followed to conduct shear tests 4-ft and 5-ft deep into the coal rib. Figure 8 shows the insertion of the shear head into the drilled hole in the coal rib. Figure 9 shows the pulling assembly mounted on the borehole collar connected to the console (Figure 7b) via hydraulic hoses.

Figure 8. Insertion of the shear head and pull bar into borehole.

Figure 10 shows the normal stress versus shear stress data points collected from the BST. A Mohr-Coulomb linear regression line is superimposed to the test data. The in-situ cohesion and friction angle of the coal at the test site are found to be 277 psi and 18.5°, respectively. The in-situ shear strength of the coal material at radial stresses of 3,942 psi and 4,042 psi are 1,596 psi and 1,629 psi, respectively. The calculated in-situ shear strength is approximately equal to the ultimate shear stress calculated by Equation 3.

LOADING CHARACTERISTICS OF MECHANICAL BOLTS FOR DIFFERENT COAL SEAMS

NIOSH researchers conducted a study to define the loading characteristics of mechanical bolts installed in coal ribs at five underground coal mines. The study was conducted for three (3) coal seams of a wide range of intact strength, including the Pittsburgh, Kellioka, and Pocahontas No. 3 coal seams. The study mines were selected based on their availability. Three (3) study mines are operating in the Pittsburgh coal seam, and one (1) study mine is operating at each of the other seams.

Figure 9. Pulling assembly mounted on the hole collar.

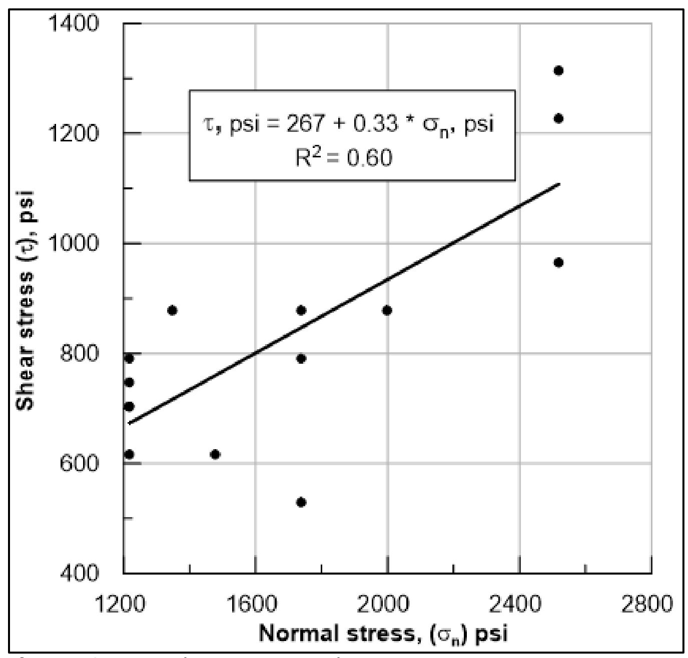
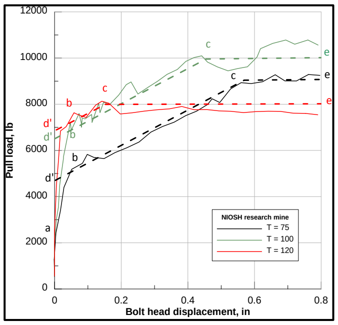


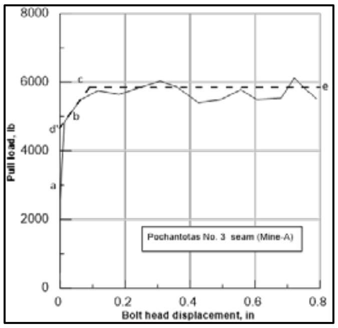
Figure 10. Normal stress versus shear stress.

Pull-out tests were conducted for bail-type mechanical bolts with a 2-inch shell. The diameter of the tested bolts was 5/8-in installed in 1-3/8-in holes. The grade of the tested bolts was 75 with yield strength of 75,000 psi. The lengths of the tested bolts was 4 ft, except those installed in the Pocahontas No. 3 seam which are 5-ft long. Depending on the accessibility and time allowed at the study site, the range of tested pre-tension loads was defined.

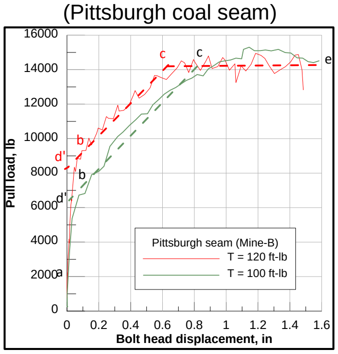
Nine (9) bolts were tested at the NIOSH Safety Research Mine. The strength of 3-in coal cubes taken from the test site is relatively low (2,252 psi) for a Pittsburgh coal seam. Three levels of installation torque were tested: 75, 100, and 120 ft-lb. The pull-out tests were repeated three times at each level of installation torque (see Table 1 in APPENDIX). Figure 11a shows samples of the measured load-displacement curves for each installation torque and the approximated tri-linear load-displacement models (dashed lines). The critical points of the tri-linear models are marked by letters a, b, c, d', and e in Figure 11a. The critical points (b, c, and d') of the nine tests are listed in Table 1.



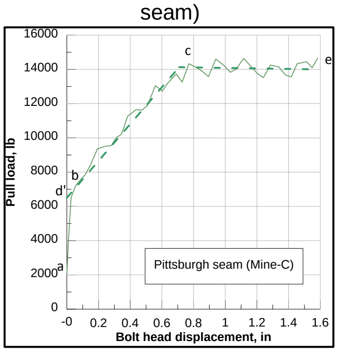
(a) NIOSH Research Mine (Pittsburgh coal seam)



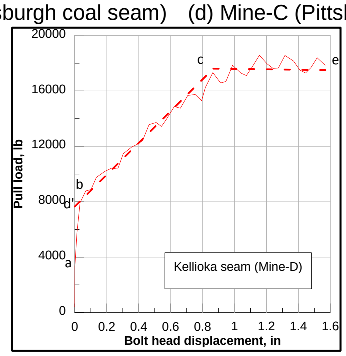
(b) Mine-A (Pocahontas No. 3 coal seam)



(c) Mine-B (Pittsburgh coal seam)



(d) Mine-C (Pittsburgh coal seam)



(e) Mine-D (Kellioka coal seam)

Critical points of tri-linear load-displacement curves

Mine	T ft-lb	Point-a	Point-b	Point-c	Point-d'
NIOSH research	75	1,800	5,185	9,132	4,790
	100	1,800	6,867	10,203	6,628
	120	1,800	7,801	9,578	7,552
A	75	2,800	5,000	5,800	5,000
B	100	1,000	6,500	14,200	6,000
	120	1,000	8,300	14,200	8,000
C	100	2,000	6,700	14,000	6,500
D	120	3,000	8,000	18,000	6,600

Figure 11. Pull-out tests conducted at different coal seams.

The observations extracted from the tests conducted at the NIOSH Safety Research Mine are: (1) the pre-tension load is directly proportional to the installation torque, (2) the anchorage capacity (load at point c) is independent of the installation torque, (3) the shear stiffness of anchorage is directly proportional to the installation torque.

Mine-A operates in the Pocahontas No. 3 seam at a depth greater than 2,000 ft. The intact strength of coal samples taken from the test site is very low (840 psi). Only full-grouted bolts are used by mine operators to support coal ribs at the study site. Because of the relatively low intact strength of the coal at Pocahontas No. 3 and the high depth of the study site, it was decided to test 5-ft-long mechanical bolts to place the anchor in solid coal. Despite having longer bolts installed at Mine-A, it was not easy to maintain the installation torque. Therefore, only two bolts were installed at a torque of 75 ft-lb. Despite the difficulty to obtain the load-displacement curves, it was possible to identify the critical points of the tri-linear load-displacement models (dashed lines) as shown in Figure 11b. The critical points of the two tests conducted at Mine-A are listed in Table 1.

Like the NIOSH Safety Research Mine, Mine-B and Mine-C are operating in the Pittsburgh coal seam. Because of the limited accessibility to those mines, only one level of installation torque was tested. A total of three (3) tests were conducted at both Mine-B and Mine-C. The installation torque for all tests was 100 ft-lb, with the exception of one test at 120 ft-lb. Figures 11c and 11d show the measured load-displacement curves and the approximated tri-linear load-displacement models (dashed lines) at Mine-B and Mine-C, respectively. The critical points of all tests conducted in Mine-B and Mine-C are listed in Table 1. As in the NIOSH Safety Research Mine, it is obvious that the anchorage capacity (load at point c) is independent of the installation torque. The anchorage capacity at Mine-B and Mine-C are about two times of that at the NIOSH Safety Research Mine, which can be explained by higher intact strength of the coal seam at Mine-B and Mine-C.

Mine-D is operating in the Kellioka coal seam, which is the strongest seam in this study. The intact strength at the study site is 4,633 psi. Because of the limited accessibility to Mine-D and its strong coal strength, it was decided to install three bolts at a high torque of 120 ft-lb. At Mine-D, it was straightforward to identify the critical points of the tri-linear load-displacement models (dashed lines) as shown in Figure 11e. The critical points of the three tests conducted at Mine-D are listed in Table 1.

The anchorage capacity (18,000–22,000 lbs) at Mine-D is the highest in this study. This can be explained by the strong coal seam at Mine-D. Pull-out tests for rib bolts installed in relatively medium to strong seams, such as Mines B, C, and D, are consistent and repeatable.

In summary, typical load-displacement curves are deduced from the pull-out test study conducted for bail-type mechanical bolts. Figure 12 shows the typical tri-linear load-displacement models of the mechanical bolts for three levels of installation torque (T1, T2, and T3).

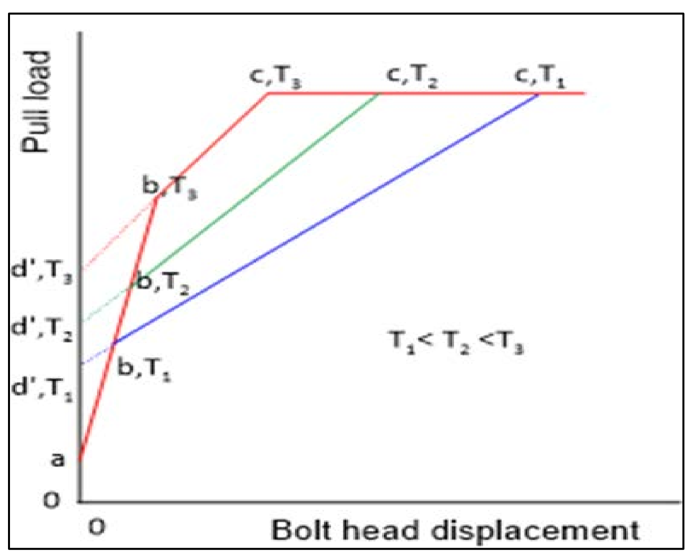


Figure 12. Typical load-displacement curves at different installation torque.

The key features of the typical tri-linear load-displacement models are:

1. The anchorage capacity (Point-c) is independent of the installation torque. The anchorage capacity depends on the strength of the coal seam and the geometry of the shell (length and diameter) as formulated in Equations 1 and 2.
2. The slope of Line b-c approximates the shear stiffness of the mechanical anchor. The shear stiffness of the anchorage is directly proportional to the installation torque; i.e. higher installation torque results in stiffer anchorage.
3. The pre-tension load is directly proportional to the installation torque. The pre-tension load can be approximated as 70% of Point-d'.
4. Point-b is the point at which the jack load and bolt load are the same.

CONCLUSIONS

NIOSH researchers conducted the study described in this paper to define the loading characteristics of mechanical bolts installed in coal ribs at five underground coal mines. Twenty-one (21) grade-75 mechanical bolts of 5/8-in diameter from a single manufacturer were used in the study. The outcome of this research provides essential data for rib support design. The main findings of this study are:

- The pull-out test mechanism for mechanical bolts was explained by measuring the induced load in the bolt via load cell and pressure transducer simultaneously. A typical tri-linear load-deformation model was obtained from pull-out tests conducted in the study mines.
- The anchorage capacity is independent of the installation torque. The anchorage capacity of the mechanical bolt is directly proportional to the strength of coal.
- The shear stiffness of the anchorage is directly proportional to the installation torque; i.e. higher installation torque results in stiffer anchorage.
- A non-linear torque-tension relationship was obtained for the 5/8-in-diameter bail-type mechanical bolts tested in a coal pillar. The pre-tension load is directly proportional to the installation torque and can be approximately determined from the tri-linear load-deformation model.

ACKNOWLEDGMENT

The authors would like to thank Mr. Todd Minoski for preparing the data collection system, Mr. Craig Compton for preparing the pull-out test gear, Mr. Timothy Matthews for preparing the borehole shear test, and Mr. Daniel McElhinney, Mr. James Addis, and Ms. Cynthia Hollerich for conducting the pull-out tests.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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APPENDIX

Table 1. Summary of critical points of tri-linear load-displacement models.

Mine	UCS, psi	Test #	Torque lb-ft	Point-b		Point-c		Point-d'	Pre-tension load, lb	Anchorage shear stiffness, lb/in
				Disp., in	Load, lb	Disp., in	Load, lb	Load, lb		
NIOSH Safety Research Mine	2,252	1	75	0.05	5,185	0.62	9,132	4,790	2,347	6,955
		2	75	0.06	5,180	0.61	7,013	5,171	4,017	2,999
		3	75	0.06	5,762	0.63	8,265	5,852	4,096	3,825
		4	100	0.05	6,055	0.41	7,918	6,310	4,417	3,923
		5	100	0.03	6,857	0.19	8,365	6,598	4,619	9,330
		6	100	0.05	6,867	0.44	10,203	6,628	4,640	8,098
		7	120	0.02	7,801	0.15	9,578	7,552	5,287	13,623
		8	120	0.02	6,845	0.14	8,124	6,795	4,757	9,371
		9	120	0.06	6,589	0.14	7,263	6,159	4,311	8,032
Mine-A	840	1	75	0.01	5,000	0.1	5,800	5,000	3,500	8,889
		2	75	0.01	5,300	0.9	9,000	4,800	3,360	4,157
Mine-B	2,500*	1	120	0.05	8,300	0.6	14,100	8,000	5,600	10,167
		2	100	0.06	6,500	0.6	13,000	6,000	4,200	11,667
		3	100	0.04	6,500	0.8	14,500	6,000	4,200	10,625
Mine-C	3,423*	1	100	0.05	8,300	0.7	13,300	6,000	5,600	10,471
		2	100	0.03	6,700	0.7	14000	6,500	4,550	10,714
		3	100	0.04	6,500	0.7	14000	6,000	4,200	11,429
Mine-D	4,633	1	120	0.04	9,000	0.8	22,000	8,500	5,950	17,105
		2	120	0.03	11,000	0.65	18,000	10,500	7,350	11,290
		3	120	0.06	9,000	1.0	18,000	8,500	5,950	9,574
		4	120	0.09	8,000	0.85	18,000	6,600	4,620	13,158

*This data was obtained through personal communication.