

LOAD BEHAVIOR OF GROUTED BOLTS IN SEDIMENTARY ROCK

By Stephen P. Signer¹

ABSTRACT

This paper presents an overview of laboratory and field tests on approximately 250 fully grouted roof bolts instrumented with strain gauges in order to study loading behavior. Laboratory work included pull tests, time-dependent tests, and shear tests. The field tests were conducted in 14 different mines extracting different commodities. However, because of the focus of this publication, only the results of tests in 9 coal mines are reported here. In the field tests, all but 14 bolts were loaded by rock movement; these 14 bolts were tested using pull gear. The variables studied included anchorage length, mechanical interlock, time-dependent behavior, shear, installation load, loading rate, and maximum load level. Such information will improve the understanding of the behavior of resin-grouted bolts, which in return will enhance the safety of miners by reducing the occurrence of rock falls. The influences of geology, overburden depth, entry width, mining-induced stresses, and bolt spacing are not described.

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INTRODUCTION

Millions of roof bolts are installed in U.S. coal mines each year to prevent ground falls. Despite the importance of entry stability, there is a lack of understanding of how roof bolts provide reinforcement to the mine rock. Bolt loads are affected by many variables, such as changes in mining conditions (geology, geometry, and in situ stress fields) and bolt properties (diameter, length, spacing, and stiffness). This lack of understanding has contributed to our inability to prevent rock falls, which remains one of the most significant safety hazards in underground mines. The Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH) has conducted research to study the behavior of grouted roof bolts and how they reduce support failure and subsequent ground falls. The purpose of this paper is to summarize important facts and principles obtained from the completed studies. Because of space limitations, we will refer to previously published material that contains detailed information on each individual test setup and variables.

The first investigation [Serbousek and Signer 1987] was a study of the axial elastic behavior of grouted bolts installed in concrete blocks. The purpose was to find out how load was transferred both between the bolt and the grout and the grout and the rock by using a known loading condition uninfluenced by geologic variations. Strain gauges were installed to measure load changes along the length of the bolt. More than 50 pull tests were performed in which applied loads were restricted to the elastic range of the bolt steel. Variations were made in hole size, bolt length, grout type, and grout strength. Results of an axisymmetric, finite-element numerical model were compared with these test results.

The second phase of research [Signer 1990] was performed at four different coal mines in Colorado, Illinois, and

Pennsylvania. Fourteen instrumented bolts were installed in sedimentary rock and tested using the same procedures as employed in the laboratory tests. In addition, these bolts were loaded to failure to study their nonlinear behavior. The purpose of this investigation was to verify the results of the axial elastic laboratory studies in the field where geology became a variable. A second goal was to study load transfer mechanisms when bolts were loaded past their elastic limit.

A third study [Signer 1988] involved laboratory tests in concrete blocks to study the creep behavior of grouted bolts instrumented with strain gauges. Variations were made in bolt length and grout type. The loads were applied with pull gear and held constant for long periods of time. The purpose of this investigation was to see if a constant load applied to the bolt head would propagate along the length of the bolt over time.

Laboratory tests [McHugh and Signer 1999] were also conducted to study the axial and bending behavior of grouted bolts subjected to horizontal joint movements. These tests were conducted on 17 instrumented bolts installed perpendicular to a joint surface in 0.6- by 0.6-m (2- by 2-ft) square concrete blocks. A shear force was applied until the bolts failed.

The last phase of research consisted of field studies in which fully grouted bolts instrumented with strain gauges were installed as supports and loaded by mining-induced stress changes [Signer and Jones 1990; Signer et al. 1993; Maleki et al. 1994; Larson et al. 1995; Signer and Lewis 1998]. These bolts were placed in 14 mines (9 coal, 2 trona, 2 gold, and 1 platinum). Variations in bolt length, bolt spacing, bolt diameter, geology, geometry, stress fields, and mining methods were recorded to study the response of grouted bolts under actual field conditions. These investigations have just been completed, and a complete data analysis is ongoing.

BEHAVIOR OF GROUTED ROOF BOLTS

BOLT LOADING

Roof bolts are loaded in four ways: axial, bending, shear, and torsion (figure 1). Torsional loading applies only to bolts that are actively tensioned by rotation and are not covered in this paper. Steel bolts are weakest in shear and strongest in axial. Although axial bolt loads result from both vertical and horizontal rock movement, most of the axial load is produced by vertical rock movement. Because there is a large difference in strength between the steel and the rock, actual shear failures of the steel are not common in sedimentary deposits. If a shear plane develops in the bolted rock mass and horizontal movement occurs, then the bolt will be subjected to a combination of axial and bending loads. A commonly observed phenomenon is the S-shaped failure shown in figure 2. This characteristic is actually a combination of axial and bending forces.

VERTICAL ROCK MOVEMENT

A grouted bolt is a passive support system, which means that bolt loads are caused by rock movements. Additional rock movement increases load on the bolt and reduces and/or stabilizes movement in the mine rock. Vertical rock movements produce axial loading in the bolt. Axial loads are transferred between the bolt and the rock by shear resistance in the grout. This resistance is the result of mechanical interlock in which load is transferred between the steel bolt and the grout and the grout and the rock via contact surfaces. Bolt hole walls have voids and irregularities created by the drilling process. Steel bolts are rolled with ribs to provide anchorage. Grout fills these irregularities and voids in the walls and bolts if the bolt has been properly installed. Localized deformation and crushing will occur in the grout at the contact points before the system

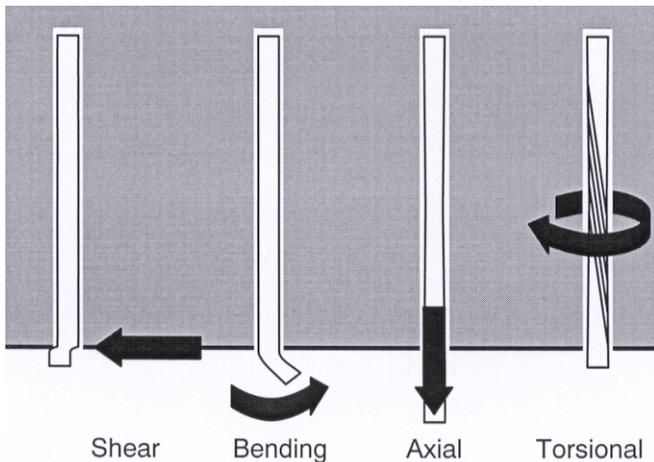


Figure 1.—Types of roof bolt loads.

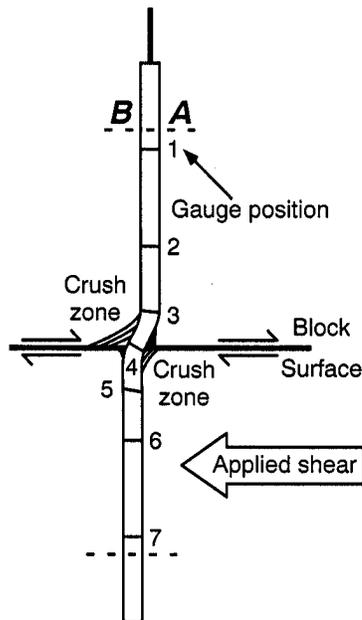


Figure 2.—Bolt response to shear movement.

tightens up, which allows additional deflection in both the bolt and the rock. Mechanical interlock will cause shear forces to be transferred from one medium to another until the maximum shear strength of the grout and/or rock is reached. At that point, the weakest material will fail, and friction will control load transfer. The rate of load transfer is similar to an exponential decay curve and is dependent on the material properties of the bolt, the grout, the rock, and the respective interfaces.

The amount of bolt length necessary to transfer the ultimate axial load capacity of the bolt to the rock is called anchorage length or critical embedment length and is a function of the strength of both the rock and the grout. If anchorage length is not long enough, then the grout or rock interfaces will fail, and the bolt will pull out of the hole.

HORIZONTAL ROCK MOVEMENT

Horizontal movement of a rock joint will compress the surrounding rock against the grout. This produces shear loads in the bolt. If the forces exceed the compressive strength of the rock, the rock will fracture. When this occurs, shear loads will be reduced and will be replaced by a combination of both bending and axial loads. Bending loads are highest near the joint and will dissipate quickly along the length of the bolt. Axial loads will travel farther along the length of the bolt than bending loads and will interact with the grout and rock as noted above.

FAILURE

Various types of failure can occur when using grouted bolts. Failure can take place in the bolt, the grout, the rock, or at the bolt-grout or grout-rock interfaces. The type of failure depends on the characteristics of the system and the material properties of individual elements.

(1) If the rock is weaker than the grout and if anchorage length is inadequate, then failure of the bolt system will occur at the grout-rock interface, which is the weakest point. As the shear strength of this interface is exceeded, then failure will progress from the point of maximum load in the bolt down the length of the bolt.

(2) If the grout is weaker than the rock, then shear failure will occur in the grout at the bolt-grout interface. If the anchorage length is inadequate, then failure will progress along the length of the bolt. Shear stress is greater at the bolt-grout interface than it is at the grout-rock interface simply because there is less area at the bolt-grout interface. The bolt-grout interface is also more prone to failure because of Poisson's effect on the steel bolt, which causes the bolt to pull away from the grout as the bolt is loaded.

(3) If there is adequate anchorage length to develop the full capacity of the steel bolt, regardless of the properties of the grout and the bolt, then the bolt will fail if loading on the bolt exceeds the ultimate strength of the steel. However, prior to bolt failure, localized grout or rock shear failure will occur. This is because the bolt, which has a greater ductility, will take larger deflections than the rock or the grout.

RESULTS

Approximately 250 bolts instrumented with strain gauges were installed in both the laboratory and the field to study loading behavior on fully grouted roof bolts. Laboratory tests included pull tests, time-dependent tests, and shear tests. Although the field tests were conducted in 14 different mines extracting different commodities, because of the focus of this publication, only the results of tests in 9 coal mines are reported here. In the field tests, all but 14 bolts were loaded by rock movement; these 14 bolts were tested using pull gear. The influences of geology, overburden depth, entry width, mining-induced stresses, and bolt spacing are not described. The following discussion covers some of the major factors related to the performance of fully grouted bolts.

BOLTS LOADED UNDER ARTIFICIAL CONTROL

Anchorage Length and Mechanical Interlock

Elastic tests in which grout type, hole size, and bolt length were varied were conducted in the laboratory on 50 bolts [Serbousek and Signer 1987]. Results on the 1.2- and 0.6-m (4- and 2-ft) long bolts indicated that 56 cm (22 in) of bolt length were required to transfer 90% of the load from the bolt to the rock (figure 3). Polyester resin and gypsum grout were used with a 19-mm (0.75-in) bolt and installed in 25-mm (1-in) holes. Nineteen-millimeter (0.75-in) bolts were also tested in 35-mm (1-3/8-in) holes using gypsum grout. The variations in grout type and hole size had no statistically significant effect.

The results from the axial elastic test conducted on grouted bolts installed in shale compared well with the results from previous laboratory work. The average anchorage length for these bolts was slightly longer than for bolts installed in concrete blocks, even though the field test results showed more variability. The roof at the first mine site contained layers of weaker rock. Test results from this mine reflected the presence of these weaker layers as changes in the rate of load transfer. A weaker layer requires a longer anchorage length compared to that needed in stronger rock. The stiffness of the bolting system decreases in weaker zones due to slip at the grout-rock interface.

Laboratory and field studies of fully grouted bolts indicate that the average anchorage length for bolts in competent rock is 56 cm (22 in). Anchorage length in weak and broken rock must be determined by field pull tests of bolts with grout lengths less than 30 cm (1 ft). Anchorage length can also be affected if the bolt hole is smooth, which reduces the effect of mechanical interlock, so that the resisting force is mostly friction. The effect of a pull test on a 30-cm (1-ft) long bolt in a smooth hole is shown in figure 4.

Anchorage length depends on the material properties of the bolt, the grout, and the rock; the quality of the installation; the smoothness of the drill hole; and possibly other factors. Weaker grout and/or rock will require longer bolt anchorage lengths.

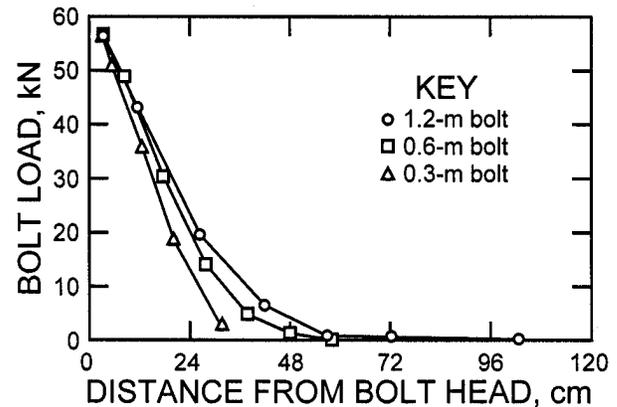


Figure 3.—Load transfer of No. 6 bolts in concrete blocks.



Figure 4.—A smooth hole lowers anchorage strength, as seen with this bolt as it pulls out of the hole.

Proper installation of the bolt is critical to the performance of the bolt. If the grout is inadequately mixed, is overspun, or is glove-fingered, then the capacity of the grout to provide mechanical interlock is severely impaired. Glove-fingering occurs when the plastic casing of the resin remains intact and causes a plastic interface between the grout and the rock. The bolt hole must be drilled with bits of appropriate sizes to produce holes of the proper diameter [Pettibone 1987].

Readings from seven bolts were averaged, and the results are shown in figure 5. Each curve represents load decay along the bolt length. The curve was established from readings of the applied load to the bolt and strain gauges. The length necessary

to transfer all the load from the bolt to the rock was the same at different load levels. The slope of each curve is an indication of the stiffness of the system. Increasing the applied load resulted in higher stiffnesses, but the load transfer length remained the same, indicating that mechanical interlock between the bolt, the grout, and the rock was the primary mechanism for transference of load. If adhesion were the mechanism of load transfer, then stiffness would be the same for all elastic loads and the anchorage length would increase as a function of applied load. Friction could not be the load transfer mechanism because bolt deflections were elastic.

Fifteen instrumented bolts were tested past the yield point of the steel to study load transfer mechanisms prior to bolt failure. The results show that yielding of the steel will translate down the length of the bolt from 23 to 51 cm (9 to 20 in), depending on rock strength, bolt hole properties, and bolt installation quality. When the bolt has yielded, load is estimated using a load strain curve that was determined experimentally. These bolts were pulled an average of 5 cm (2 in) before failure.

Time-Dependent Behavior

Laboratory tests were conducted on six bolts to determine the time-dependent properties of grouted bolts. These bolts were instrumented with strain gauges and installed in 2.5-cm (1-in) holes with both gypsum and resin grout. Bolts that were 1.2, 0.6, and 0.3 m (4, 2, and 1 ft) long were tested at applied loads of 40, 58, 80, and 102 kN (9,000, 13,000, 18,000, and 23,000 lb). The strain gauges were monitored constantly to detect load changes along the bolt. Load was applied with hydraulic rams and maintained with hydraulic accumulators for a period of at least 1 month, or until the bolt stabilized.

Figure 6 shows the results for the 1.2-m (4-ft) long bolts. To determine the rate of load change per day, a linear fit was done at each strain gauge location beginning at day 10 and continuing to the end of the test. The resulting values were normalized by dividing the rate of load change per day by the load on the bolt at a given location. When the load on the bolt approached zero, the data were deleted because of problems caused by dividing by zero. Bolts installed with gypsum grout showed three to five times more creep than bolts installed with resin grout.

Shear Tests

Laboratory tests on 17 bolts were conducted to study the behavior of roof bolts subjected to shear loading over a range of axial bolt loads. Fourteen strain gauges were attached to each bolt to measure both axial and bending loads. The instrumented bolts were grouted through two high-strength concrete blocks, and axial tension up to 75% of the yield strength was applied to the bolts. The block interface was smooth and acted as the failure plane. Shear loads were applied to the blocks until the bolts failed due to shear movement of the joint. The tests characterized the relationship of axial and bending loads on the bolt to shear forces across a rock bedding plane.

The results showed that (1) axial bolt loading had little to no effect on the capacity to resist shear loading of a joint, (2) the bolts failed as a combination of axial and bending loads rather than shear loads, (3) the bending loads caused by joint movement dissipated within a few inches of the joint, but axial loads were transferred along the bolt length for the distance of the anchorage length, and (4) all but one bolt failed within 5 cm (2 in) of horizontal movement of the joint.

BOLTS LOADED BY ROCK MOVEMENT

Installation Loads

When a fully grouted bolt is installed, the upward thrust of the roof bolter will compress the weakest rock layer in the immediate roof. The amount of compression will depend on the distance from the roof line, the strength of the surrounding rock layers, and the amount of upward thrust of the roof bolter. The bolt will be held in place until the grout hardens. When the force from the roof bolter is removed, the compressed roof rock will rebound, which produces a resisting force in the grouted bolt.

Installation loads on 40 strain-gauged roof bolts from 4 different coal mines are shown in figure 7. The data represent an average of 420 strain gauges. Some bolts had 10 strain gauges per bolt, and some bolts had 12 strain gauges per bolt. The average installation load was 11 kN (2,400 lb) with a standard deviation of 8.5 kN (1,900 lb). This means that installation loads tended to vary from zero to 20 kN (4,500 lb).

The highest initial load was usually near the roof line and decreased as the distance from the roof line increased. The amount of force developed depended on the properties of the immediate roof, the ability to apply the upward thrust of the roof bolter, and the behavior of the roof bolter operator. That is, often a bolter operator would not apply the same amount of thrust to the specially instrumented roof bolts as to a normal bolt. The amount of time elapsed from installation to the first measurement could affect the readings if the mine roof were active. If the hole was not drilled deep enough, the bolt could bottom out.

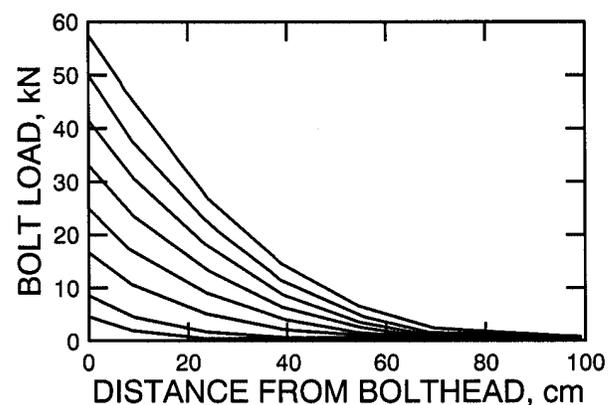


Figure 5.—Results of pull tests on instrumented bolts.

Loading Profiles

Figure 8 shows axial loading behavior of a typical fully grouted roof bolt. When the bolt is first installed, there is an initial load that varies along the length of the bolt. As mining progresses, redistribution of rock stresses change the stress pattern in the immediate mine roof. A fully grouted bolt

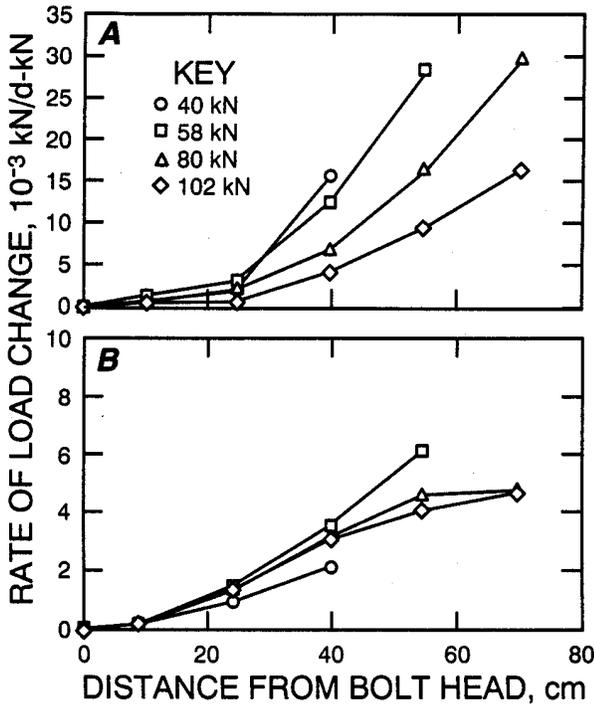


Figure 6.—Time-dependent behavior of (A) gypsum-grouted bolts and (B) resin-grouted bolts.

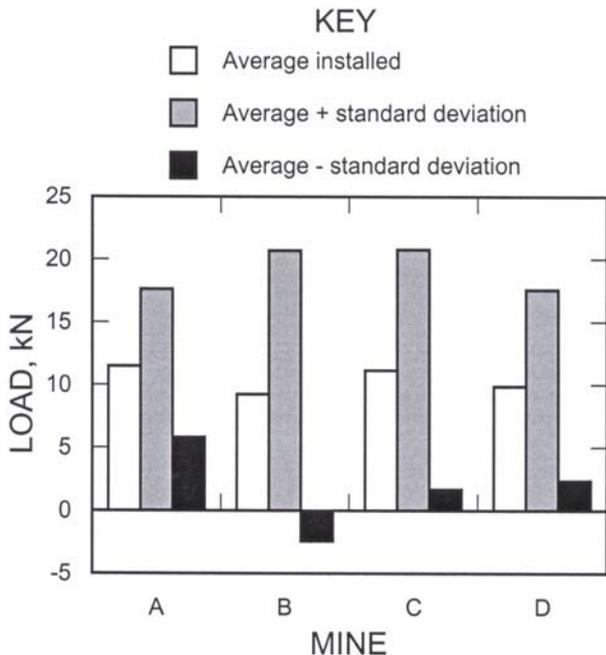


Figure 7.—Installation loads on instrumented bolts.

responds to the stress changes by increasing in load. The distribution of load along the length of the bolt varies in proportion to the stress pattern. After primary mining has reached a sufficient distance away from the test area, the load on the bolt increases at a slower rate, stabilizes, and in some cases decreases. If secondary mining occurs and the immediate roof is within the zone of influence from abutment stress changes, then the bolts will go through the same cycle of load increase and stabilization. This sequence assumes that there are enough bolts installed to cause the immediate roof to stabilize.

Loading Rates

The rate at which grouted bolts increase in load depends on the rate of rock movement in the immediate roof. Stress changes in the rock result in movement. The amount of movement depends on the rock and joint modulus and strengths. Strain gauges on bolts can measure rock movement several orders of magnitude finer than can other deflection measurement systems. For example, 0.05 mm (0.002 in) of movement in a bolt section 2.5 cm (1 in) long will result in 2,000 microstrain, which is the yield strain for a No. 6 slotted bolt.

Initial loading rates on 62 strain-gauged roof bolts installed in 6 different coal mines are shown in figure 9. The initial loading rate was calculated by a linear fit of the change in axial loads right after installation. The duration of this loading rate varied significantly from one site to another, as did the load level attained during initial loading.

The average rate of change of bolt load resulting from entry development varied from 1 to 16 kN/d (250 to 3,500 lb/d). Each bar on the graph represents an average of all the strain gauges at each mine site. Each site had significant variations in loading rates among bolts and even among gauges on each bolt. The maximum loading rate at each site is significant because highly

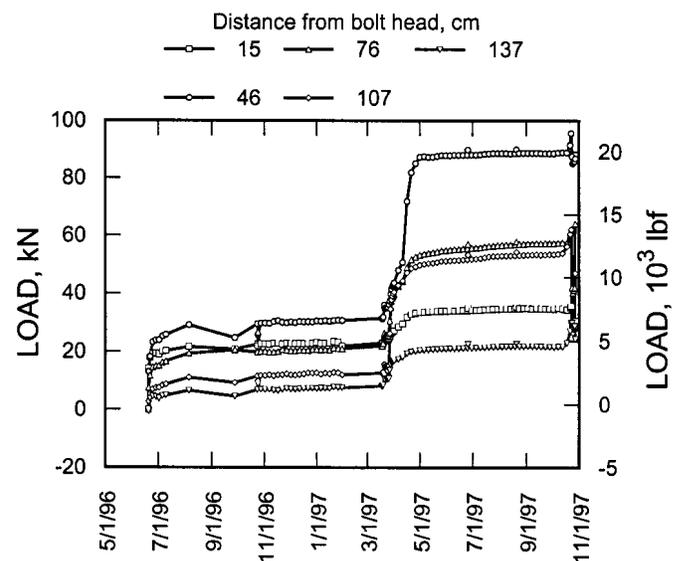


Figure 8.—Typical bolt load response to mining-induced stresses.

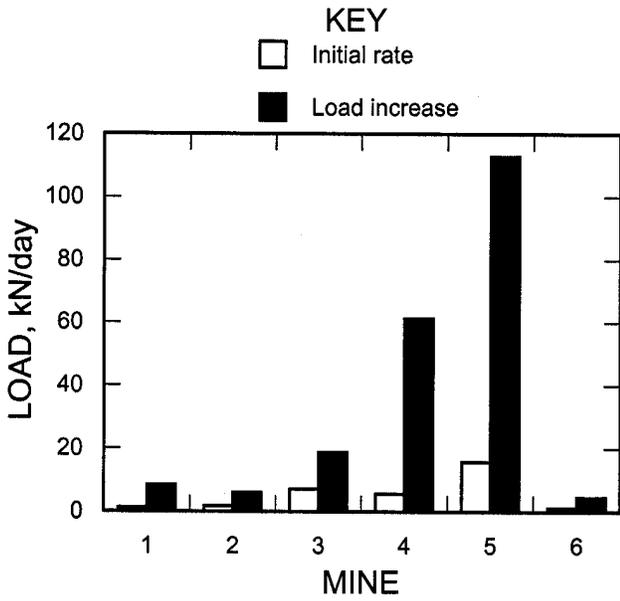


Figure 9.—Initial load rate and rate of bolt load increase after installation.

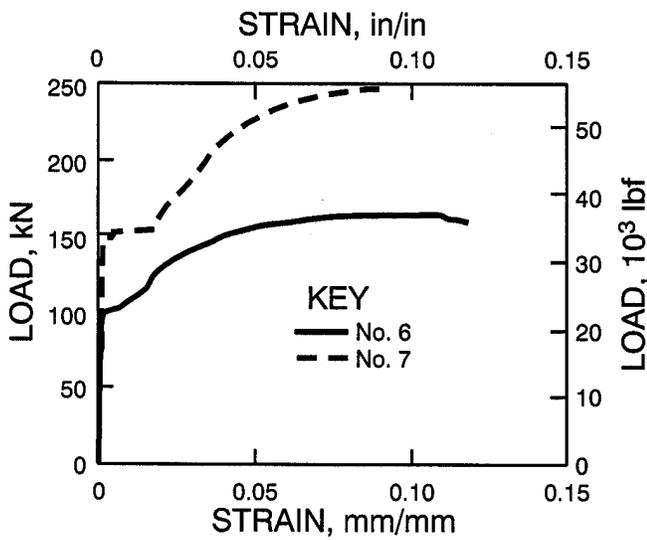


Figure 10.—Strain-load curve for No. 6 and No. 7 slotted bolts.

Table 1.—Properties of bolts

Bolt type	Yield load		Ultimate load		Cross-sectional area	
	kN	lb	kN	lb	cm ²	in ²
No. 6	107	24,000	176	39,500	2.58	0.40
No. 6, slotted . .	96	21,500	160	36,000	2.38	0.37
No. 7	160	36,000	270	60,500	3.87	0.60
No. 7, slotted . .	149	33,500	249	55,900	3.61	0.56

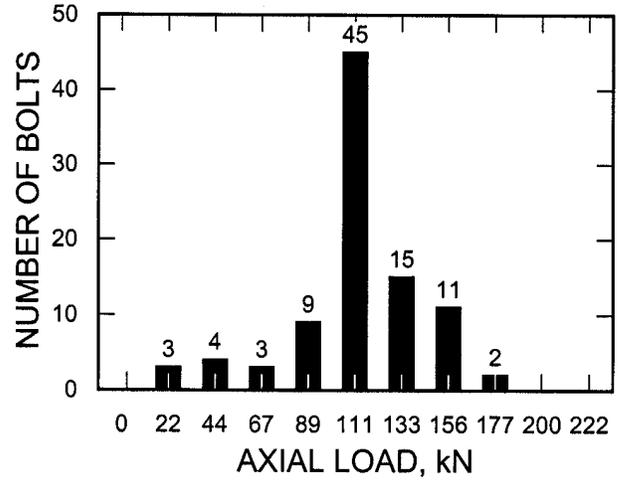


Figure 11.—Maximum axial loads on bolts in all coal mines.

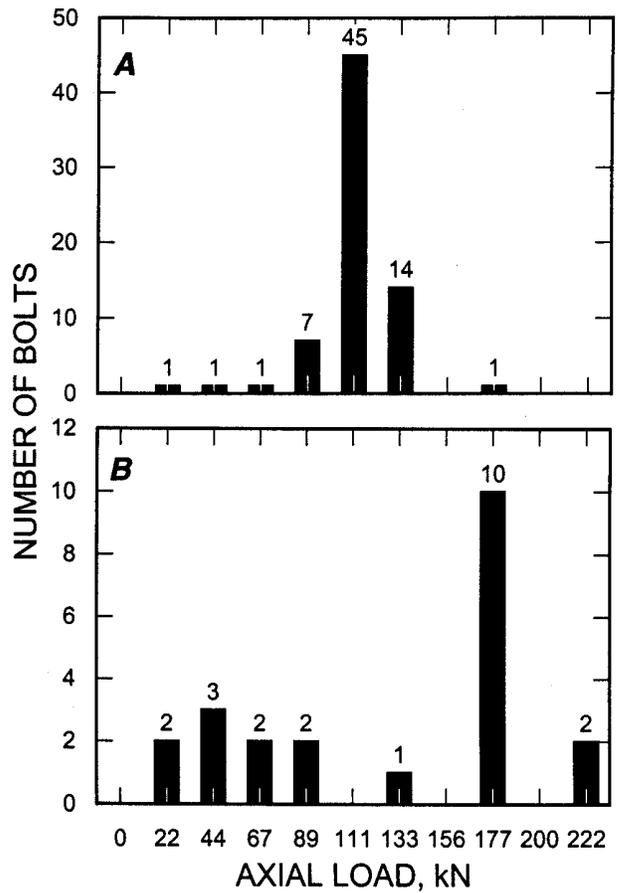


Figure 12.—Maximum axial loads on (A) No. 6 bolts and (B) No. 7 bolts.

loaded bolts fail first. The maximum loading rate after bolt installation varied from 4.4 to 105 kN/d (1,000 to 23,500 lb/d). There are many factors that cause these variations, including geology, seam height, entry width, pillar size, and stress field.

MAXIMUM BOLT LOADS

Figure 10 shows the load-strain behavior of slotted bolts, and table 1 compares the yield and ultimate strengths of slotted bolts and regular rebar bolts. Bolt row spacing for the instrumented bolts was reduced to compensate for the 10% reduction in strength. In some cases, the instrumented bolts were installed as supplementary support. Also, No. 7 strain-gauged bolts were sometimes installed where No. 6 bolts were used as the support system.

The distribution of maximum axial loads, i.e., the maximum load on each instrumented bolt, is shown for all bolts installed

in coal mines in figure 11 and for No. 6 bolts and No. 7 bolts in figure 12A and 12B, respectively. This value, rather than average load, is what would cause a bolt to break. Maximum axial load on the majority of the bolts exceeded the yield point of the steel, but was less than ultimate load. Maximum load on the instrumented bolts can be used as an estimate for selecting bolt size and spacings.

These data represent loading on 92 instrumented bolts at eight different mine sites. Seventy-five percent of the instrumented bolts reached the yield point of the steel on at least one gauge location, and 50% of the bolts exceeded the yield point of the steel. These values represent bolt loading resulting from a variety of loading conditions. Most were installed in longwall gate road entries; loading represents both passes of the longwall. Fourteen bolts were installed in a longwall recovery room where the roof support failed.

CONCLUSIONS

The anchorage length for grouted bolts installed in competent rock is 56 cm (22 in) and is established by mechanical interlock of the grout. Bolts loaded to failure show that yield will translate down the length of the bolt from 23 to 51 cm (9 to 20 in) and will be deflected an average of 5 cm (2 in) before failure. Load creep on bolts installed with polyester resin grout was shown to be minimal compared with creep on bolts installed with gypsum grout. Results of shear tests showed that the bolts failed from a combination of axial and bending loads rather than shear loads and that axial bolt loading had little effect on the capacity to resist shear loading of a joint.

The average load on fully grouted bolts just after installation was 11 kN (2,400 lb) and increased anywhere from 1 to 105 kN/d (250 to 23,500 lb/d). The data representing 92 instrumented bolts at 8 different coal mine sites showed that 75% of the bolts reached the yield point of the steel (0.2% strain) and 50% of the bolts exceeded the yield point of the steel.

The results of this study will increase understanding of the behavior of roof bolts in underground mines, which in turn will enable miners to select the appropriate bolts for reducing roof falls, thereby increasing workplace safety.

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