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**UNITED STATES DEPARTMENT OF THE INTERIOR**
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## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| ft | foot | lb/in | pound per inch |
| in | inch | min | minute |
| lb | pound | pct | percent |
| lbf | pound force | psi | pound per square inch |

# LINEAR LOAD-TRANSFER MECHANICS OF FULLY GROUTED ROOF BOLTS

By M. O. Serbousek[1] and S. P. Signer[2]

## ABSTRACT

The load-transfer mechanics of fully grouted roof bolts in coal mines have been investigated in laboratory and analytical studies. The purpose of this Bureau of Mines research is to increase understanding and better interpret data from routine field pull tests and to develop a numerical model of a grouted bolt that can be used in a global computer model of a mine roof. Analytical studies using closed-form solutions and finite-element techniques were compared to experimental results.

Laboratory work includes variation of bolt length, hole diameter, and grout type. Pull tests were performed on 4-, 2-, and 1-ft bolts in holes of 1- and 1-3/8-in diameters. Both polyester resin and inorganic grouts were used as the anchorage medium. Strain gauges were installed on the bolts at several locations to observe the rate of load transfer from the bolt through the grout to the rock mass when a force was applied at the bolt end using standard jack pull testing procedures and equipment. The average anchorage length of 4- and 2-ft bolts was 22 in. Grout type and hole size variations did not produce a significant effect on the rate of load transfer from the bolt to the rock.

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## INTRODUCTION

Fully grouted untensioned roof bolts are one type of roof support system used in underground mines to prevent structural failure of the mine roof. Adequate analytical design methods for the length and spacing of roof bolts are not available for various ground conditions even though the use of these bolts is increasing. Numerical modeling is one design approach; however, this method requires a better understanding than is currently available of the mechanics involved in the transfer of load between the bolt and the mine rock. The objective of this study is to increase the understanding of the load-transfer mechanics of fully grouted bolts through comparisons of numerical models with laboratory results.

Grouted roof bolts have been increasing in use in the United States since the 1970's and now account for approximately 35 pct of the bolts installed in underground coal mine roofs. Resin costs have decreased despite inflation, so the use of this means of roof support will probably continue to increase. This necessitates an adequate design method.

Presently, the bolting patterns for the required roof control plans are based upon past practices, which are derived from trial and error. This can result in overdesign or underdesign. Overdesign causes unnecessary cost, and underdesign can result in roof falls. Numerical modeling is one solution to this problem. A numerical model might be used to determine effective spacing and length of bolts by taking into account such factors as geology, joint discontinuities, time effects, mine geometries, and in situ field stresses. Types of numerical models include finite elements, boundary elements, and finite differences.

The state of the art in numerical modeling is currently not adequate to design bolting patterns in coal mine roofs using grouted bolts. This design problem is complex and does not lend itself to an easy numerical solution. Some of the problems involve the necessity for adequate determination of rock properties, the modeling of the discontinuities, the determination of existing stresses, and modeling the structure in the post-elastic regime. The modeling of grouted bolts poses some particular problems. For example, the bolt does not produce a significant effect on the global model until a large amount of deflection has taken place. This means the rock may have joint discontinuities or be in a plastic phase. Neither of these situations is currently modeled accurately with numerical techniques. Another problem with using numerical techniques to simulate the effect of a grouted bolt in a mine roof is the lack of an adequate global model of a grouted bolt. Development of such a model necessitates adequate definition of the interaction mechanics between the bolt and the mine roof.

A typical full-column roof bolt is shown in figure 1. Polyester resin is commonly used as the grout, but epoxy resin and inorganic grouts have also been

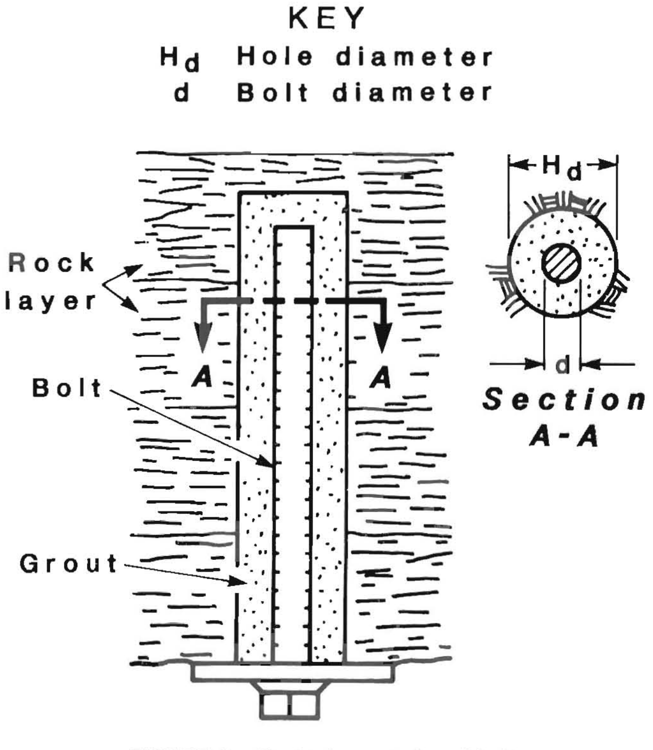

FIGURE 1.—Typical grouted roof bolt.

developed (1-2).[3] A fully grouted bolt is a passive roof support system that is activated by movements of the mine rock. The resin bolt has provided support in areas where mechanical bolts are not effective. Several theories have been formulated to explain how roof bolts function in ground support (3-7), such as by suspension and beam building, etc. Briefly, suspension produces axial forces in the bolt, and beam building adds a shearing force to the bolt system.

The behavior of ground support systems using grouted roof bolts has been studied by numerous people (4, 8-13). Numerical models of grouted bolt systems have been created and compared with experimental results (4, 14). A grouted bolt element was also developed (15-16) for a global finite-element model. However, the mechanics of interaction between the components of the grouted bolt system (bolt, grout, and mine rock) have not been well defined or verified.

This project studied how the load is transferred between each element of the bolting system. Laboratory pull tests on grouted bolts have been compared to a finite-element model of a discrete bolt. For the numerical model to be valid, both equilibrium and compatibility must be satisfied. A fully grouted bolt can resist both shear and axial deflections and have both an elastic and a plastic response to load. This paper will discuss only the axial linear elastic response of the bolt system. Work is in progress on the plastic and time-dependent properties of the grouted system. The ultimate goal of this project is to develop a numerical model of a grouted bolt that can be used in a global model of a mine.

## ACKNOWLEDGMENT

The authors wish to express their appreciation to Dan Sanders, engineering technician (retired), of the Bureau's Spokane Research Center for his assistance in strain gauging and laboratory testing during this investigation.

## LOAD-TRANSFER MECHANICS

The fully grouted bolting system consists of three materials: the bolt, the grout, and the mine rock. Each component has different material properties. The steel bolt is ductile and has a high ultimate strength and modulus of elasticity. This means that it can take a large load and deflection. The grout and mine rock are weaker and have lower ultimate strengths and moduli. They are generally brittle and will not take high-tension loads. This can lead to shear failures. However, if there is adequate anchorage length, then the full capacity of the steel bolt can be utilized even though the grout and the host rock are weaker.

The redistribution of forces along the bolt is the result of movement in the roof. This movement may be lateral and/or axial with respect to the bolt length. When movements occur, load is transferred to the bolt via shear stress in the grout. The bolt will help prevent collapse of the immediate roof if there is adequate anchorage length and if failure does not occur in the grout or bolt. The location of failure will depend on (1) the material properties of the components, (2) the characteristics of the installed bolt (grout quality, type of roof rock, installation procedures, etc.), and (3) the location of discontinuities in the roof rock.

A typical fully grouted bolt is a passive reinforcement system that does not apply any active force to the mine roof. This means that the bolt provides reinforcement when movement takes place in the rock. Additional movement increases the load in the bolt and reduces the rate of movement in the mine rock. This process takes place through transfer of the developed load to stable rock. The anchorage length is the length of grouted bolt necessary to transfer all the developed load from the bolt via the grout to the rock. If the anchorage length is not long enough, then the grout or rock

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[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

can fail. A slab separation produces forces in the bolt that are primarily axial, whereas the stresses in the grout and rock are shear.

Various types of failure can occur using grouted bolts. Failure can take place in the bolt, the grout, the rock, the bolt-grout interface, or the grout-rock interface. The type of failure depends on the characteristics of the system and the material properties of the individual elements. Figure 2 shows several possible failure modes of fully grouted bolts due to the axial loading of a slab separation. The conditions shown for bolt *A* could result from grout failure. Bolt *B* has adequate anchorage length, yet the applied load exceeded the ultimate strength of the bolt. The illustration for bolt *C* shows an instance of failure due to inadequate anchorage length. A standard pull test would not give an indication of these possible failures because only the portion of bolt near the bolthead is being evaluated. A pull test on bolt *A* could indicate both adequate strength due to the bolt length above the separation and additional deflection if the grout had already started to weaken. However, this additional deflection may be indistinguishable.

The properties of the system are important in determining the location of failure. For example, the shear stress at the bolt-grout interface is greater than the shear stress at the grout-rock interface because the effective area is smaller. This means that if the grout and rock have similar strengths and if the required anchorage length is inadequate, then failure could occur at the bolt-grout interface. If the mine rock is weaker, then the failure could happen at the grout-rock interface. If the anchorage length is sufficient to develop the full capacity of the steel, then the bolt will rupture if the applied loads exceed the ultimate tensile capacity of the bolt. In the tests described here, the applied load was limited to the elastic response of the system so that failure did not occur. The interactions between the bolt and the grout and between the grout and the rock are primarily mechanical interlock in the elastic regime. The instrumented bolts were recovered from the test blocks, and examination of the resin bond showed no chemical adhesion of the grout. As movement takes place, the irregularities on the surfaces of the steel bar and the hole cause mechanical interlock. The interlock will cause shear forces to be transferred from one medium to another until the maximum shear strength is reached. At that point, the weakest material will fail and then friction will control the load transfer. The rate of transfer of load from the bolt to the rock is similar to an exponential decay curve and is dependent upon the material properties of the bar, the grout, the rock, and the respective interfaces. The load-transfer rate is the change in bolt load with respect to the change in distance along the bolt.

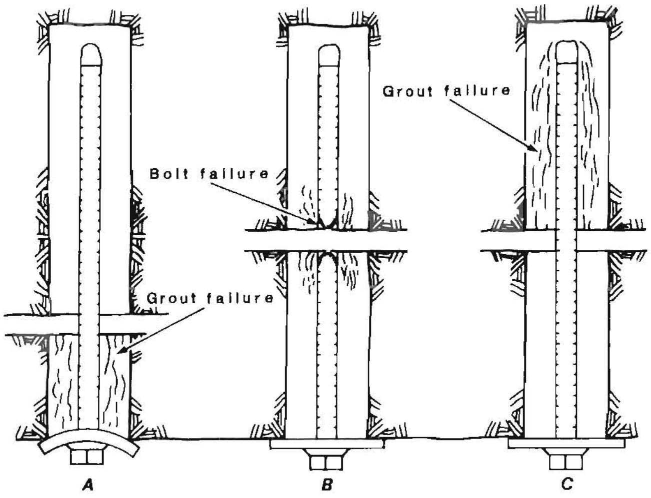

**FIGURE 2.—Possible failure modes of grouted bolts.**

## ANALYTICAL ANALYSIS

A mathematical model of a grouted bolt must satisfy both equilibrium and continuity criteria in order to accurately simulate the effect of the bolt in a global model of a mine roof. Work has been done in the past to address this problem, and both analytical equations and finite elements have been proposed (4, 12). Various closed-form decay formulas have been developed to describe the rate of load transfer from the bolt to the rock medium.

One basic closed-form solution is

$$\sigma = \sigma_0 e^{-\alpha y},$$

where $\sigma$ = stress in the bolt at a distance y, psi,

$\alpha_0$ = stress at the point of applied force, psi,

$\alpha$ = decay coefficient, which depends on the stiffness of the system, 1/in,

y = distance along the bolt from the applied force, in

and $\alpha = 4P/\pi VEd^2$,

where P = load applied at the bolthead, lbf,

d = the diameter of the bolt, in,

E = the modulus of the bolt, psi,

and V = the deflection at the head of the bolt, in.

Figure 3 shows an elemental view of these variables. This type of analytical model assumes that (1) there is complete bonding between the bolt-grout and grout-rock interfaces, (2) elastic deformation takes place both in the bolt and in the grout, and (3) the rock has no deflection. Also, the analytical model does not include the length of bolt as a variable. These restrictions may be unrealistic.

A finite-element model (FEM) can be used to provide an approximate solution without some of the limiting restrictions imposed by the closed-form solutions. To study the interaction mechanics in detail, a linear FEM was made of a discrete bolt. The accuracy of the model is dependent on the size, type, and orientation of the elements. For this model, an axisymmetric element was chosen because it simulates the real problem.

The boundary conditions for the selected FEM are shown in figure 4 and simulate an experimental pull test. The top and bottom are free surfaces with the sides rollered to prevent radial translation. The reactive support of the pull

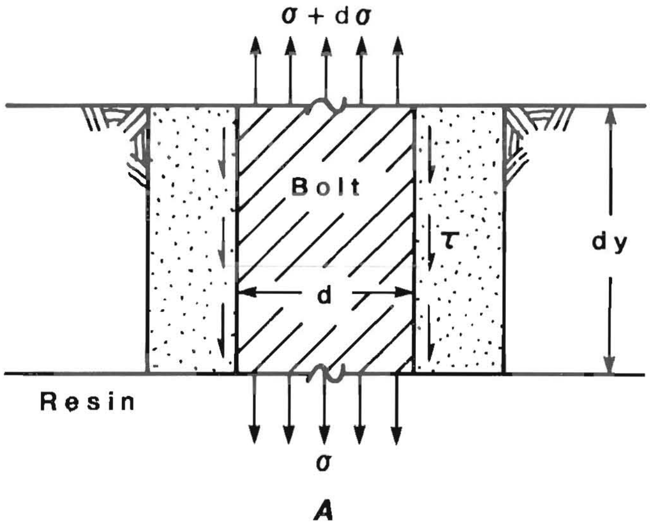

FIGURE 3.—Variables used in closed-form solution.

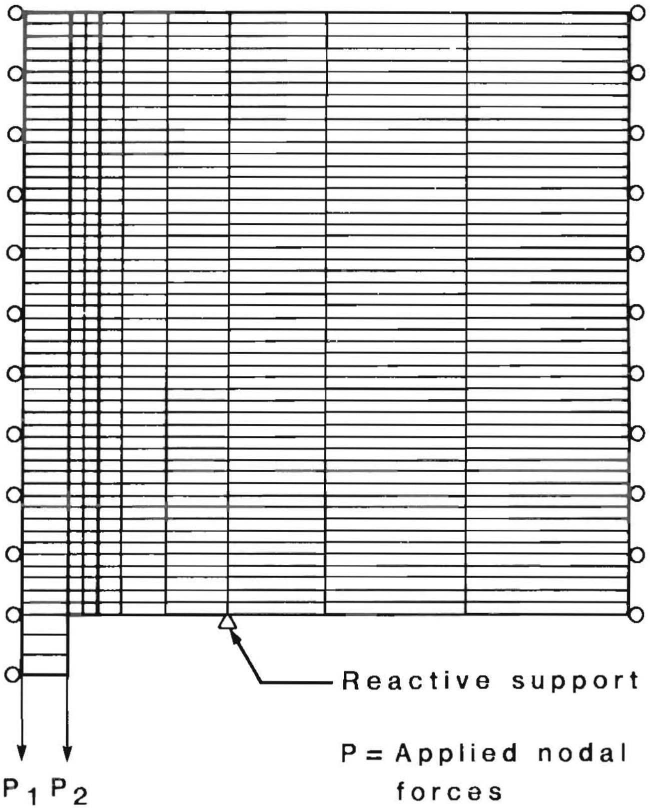

FIGURE 4.—Boundary conditions for finite-element model.

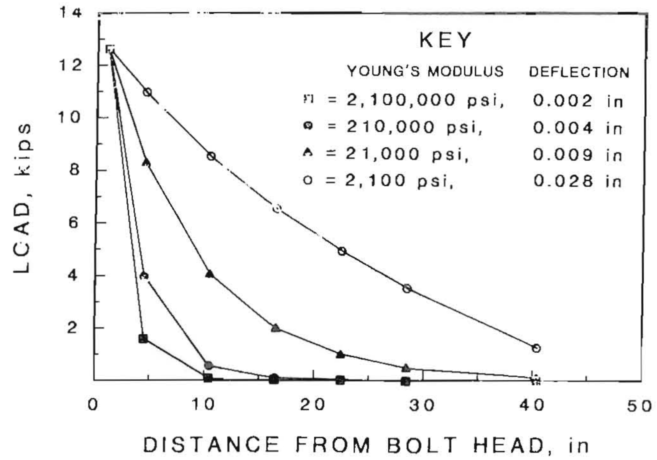

**FIGURE 5.—Variations in grout modulus with constant rock modulus.**

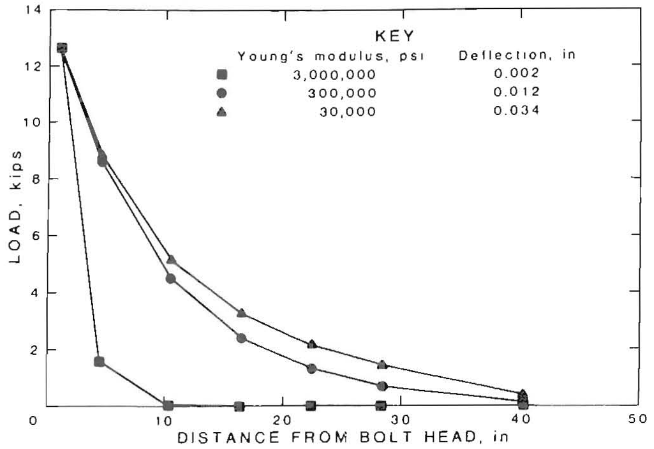

**FIGURE 6.—Variations in rock modulus with constant grout modulus.**

gear is simulated with a restraint in the vertical direction. The mesh size was varied to optimize accuracy and computer time.

The deflection at the head of the bolt depends on the moduli of the materials. The results of several FEM are shown in figures 5 and 6. These figures demonstrate how the load transfer rate and the resulting deflections at the head of the bolts are dependent on the grout and rock moduli.

## EXPERIMENTAL DESIGN

Pull tests are routinely performed on roof bolts in underground mines for anchorage evaluation. This study used a standard pull-test procedure to study the transfer of load from the bolt to the rock. The rate at which load was transferred out of the bolt and into the rock was measured with instrumented roof bolts.

The bolts used in this study are slotted with two continuous cuts along the length of the bolt in which strain gauges are attached. Each slot is 1/4 in wide and 1/8 in deep. This configuration allows up to six gauges to be located on one side of the bolt (fig. 7). Table 1 shows the gauge locations for 4-, 2-, and 1-ft bolts. The limiting factor for the number of gauges is the amount of space required for the connecting wires. The gauges were placed in pairs on each side of the bolt to account for any bending effects and to provide redundancy. All bolts were from the same lot and were grade 50 (yield load [Py] = 22,000 lbf), standard deformed 3/4-in-diam bolts with forged heads.

Typically, instrumented bolts measure strain, and then the load is calculated by using the modulus of elasticity and

TABLE 1. - Gauge locations for 4-, 2-, and 1-ft bolts

| Grouted bolt length | Distance from bolt head to gauge pairs, in | | | | | |
|---|---|---|---|---|---|---|
| | D1 | D2 | D3 | D4 | D5 | D6 |
| 4 ft.......... | 4.5 | 10.5 | 16.5 | 22.5 | 28.5 | 40.5 |
| 2 ft.......... | 3.0 | 7.0 | 11.0 | 15.0 | 19.0 | 23.0 |
| 1 ft.......... | 2.0 | 5.0 | 8.0 | 12.5 | NAp | NAp |

NAp Not applicable.

NOTE.--Embedded distance is 1 in less due to the use of pull collars.

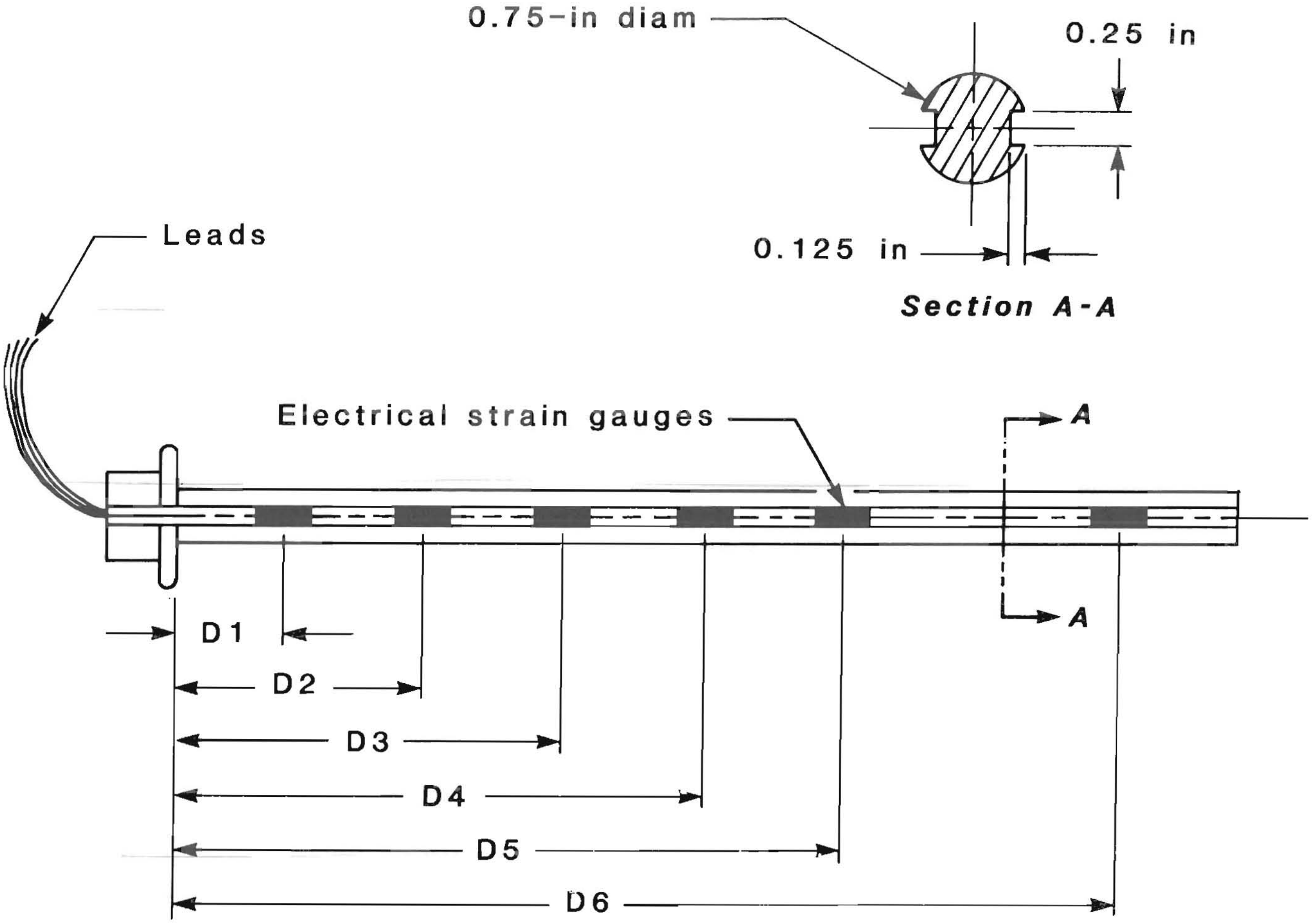

FIGURE 7.—Gauge locations for instrumented bolts.

the area of the bolt. This method presents a problem because area is not well defined in these bolts, and gauge alignment is critical in order to obtain accurate results. The bolts used in this experiment were instrumented with strain gauges and then were calibrated in a uniaxial tension machine (fig. 8) to correlate voltage change directly with load, using statistical methods. This technique eliminates the problems of area reduction, gauge location, and local inconsistencies in the bolt.

The calibration procedure involved a linear statistical regression analysis to establish the relationship between applied load and voltage change. To ensure accuracy, data were taken from three loading cycles for the calibration of each bolt. The applied load was limited to the elastic range of the steel. The voltage change for each gauge was statistically correlated to the load in order to obtain a slope and an intercept. If variations larger than 0.5 pct were encountered, the gauge was replaced. Calibrations for each gauge on each bolt were stored in a computer file and were used to automatically reduce the experimental voltage readings to values for load and to plot the results without manual data manipulation. Typically, the standard deviation of the predicted load value using a least squares linear fit was approximately ±50 lb. This means that the strain gauges on the bolt will measure the load to within 100 lb. This procedure produced excellent test results with good repeatability.

The bolts were installed in 2- by 2- by 4.5-ft concrete blocks, which were used to simulate roof rock. These blocks were produced from a concrete mix with a 3/8-in maximum aggregate size, purchased from a local premix plant. The typical uniaxial compressive strength of the

FIGURE 8.—Calibration of instrumented bolts.

mix was 4,500 psi. The holes were drilled using a mast-type rotary roof drill (fig. 9).

The gypsum-grouted bolts were installed by inserting a gypsum grout slurry into the hole and subsequently placing the bolt into this mixture. The resin-grouted bolts were installed following the manufacturer's recommended procedures.

Figure 10 shows the pull gear arrangement. The pull gear consists of a pull collar placed at the bolt head. Over this collar, the crow's foot is attached. It, in turn, is connected to a threaded rod. The force is applied to the head of the bolt by a hydraulic ram. The hydraulic pressure is supplied by a hand pump. The applied force is monitored with a pressure gauge and a pressure transducer.

When the load is applied to the system, the bolt head will deflect. These deflections are measured at the end of the pull gear by a dial gauge that is accurate to within 0.001 in. For these experiments, the force was applied to the bolthead incrementally from 920 lbf to 12,800 lbf. The applied force at the bolthead was maintained at each level for 5 min in order for the system to stabilize before readings were taken. The maximum applied force is approximately 80 pct of the yield of the bolt. Three loading cycles were conducted for each test. The data were reduced using statistical techniques and were plotted to determine the force in the bolt at the six gauged stations.

## EXPERIMENTAL RESULTS

Laboratory test results are based on the averages from 48 pull tests (appendix). The grout type, hole size, and bolt length were varied to determine results for various conditions. The data from a typical test are shown in figure 11. Each curve represents the load decay along the bolt length. The curve is established from the jack load and strain gauge results. The length necessary to transfer all of the load from the bolt to the concrete is the same for different load levels. The slope of each curve is an indication of the stiffnes of the system. Increasing the applied load results in higher stiffness, but the load-transfer length remains the same. This indicates that mechanical interlock between the bolt, the grout, and the concrete is the dominant mechanism for load transfer. Figure 12 presents the standard deviations of the data from all 4-ft bolts. Those tests in which grout type and hole size were varied had no statistically significant variations in the results. For example, figure 13 shows little difference between the behavior of resin grout and that of gypsum grout for 4-ft bolts. However, changes in bolt length did produce significant variations in results (fig. 14). Both 4- and 2-ft bolts had an anchorage length of 22 in with a slight variation in the transfer rate. The 1-ft bolts had a shorter anchorage length and a steeper transfer rate.

## COMPARISON OF ANALYTICAL RESULTS TO EXPERIMENTAL DATA

To compare a numerical model with the experimental results, both the equilibrium and the compatibility conditions for the model must be satisfied. This means that the model must use the proper constitutive equations and match the experimental deflections and stress distributions. Unconfined compression tests were run on the concrete and on the gypsum grout to determine values for Young's modulus and Poisson's ratio (table 2),

TABLE 2. - Experimental modulus values

| | Young's modulus (E), $10^6$ psi | Poisson's ratio ($\nu$) |
|---|---|---|
| Steel............... | 29 | 0.3 |
| Concrete............ | 3.0 | .2 |
| Grout............... | 2.1 | .25 |

FIGURE 9.—Drill stand for drilling boltholes and installing roof bolts.

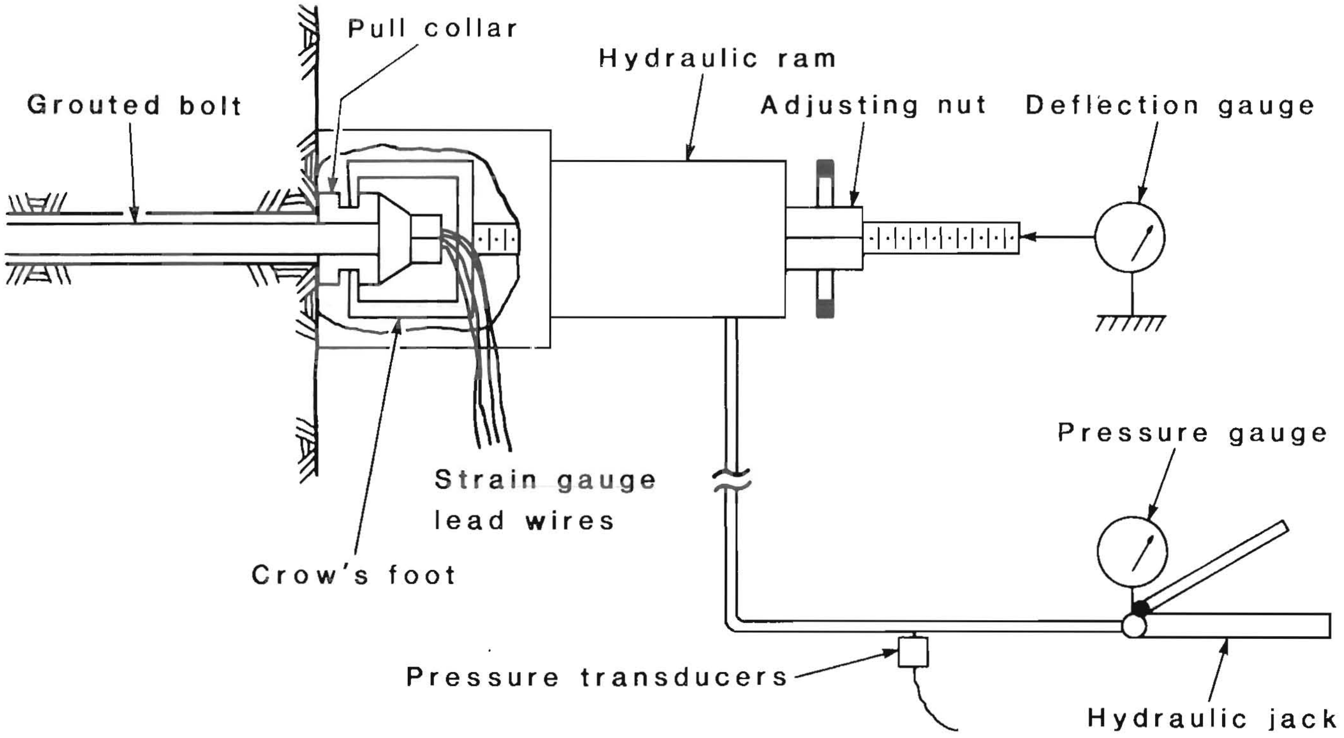

FIGURE 10.—Pull gear.

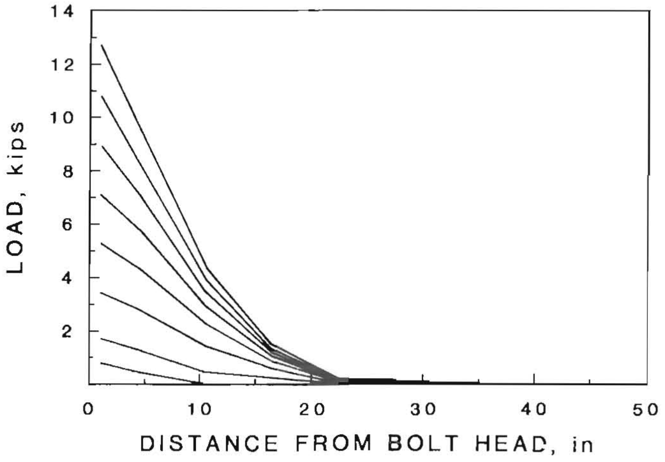

FIGURE 11.—Typical test results.

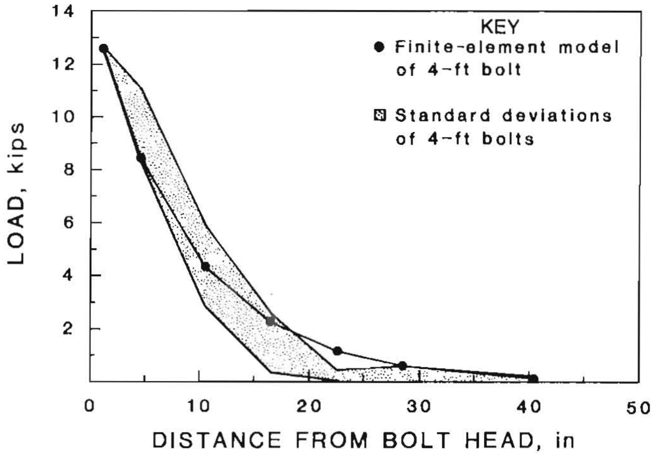

FIGURE 12.—Comparison of finite-element model with experimental results.

and the established values for steel were used for the steel bolt. No property tests were performed on the resin.

The deflection of the numerical model can be adjusted by varying the moduli of the materials (figs. 5 and 6). The average experimental deflection measured at the bolthead was approximately 0.040 in. To match the experimental deflections, either the grout modulus must be reduced by a factor of approximately 1,000, or the rock modulus must be reduced by a factor of 100. This reduction is not reasonable. Possible causes of the discrepancy between the numerical model and the experimental results include deflection induced by elastic deformations of the pull gear, seating of the pull collar on the bolthead, and movement between the bolt-grout and grout-rock interfaces.

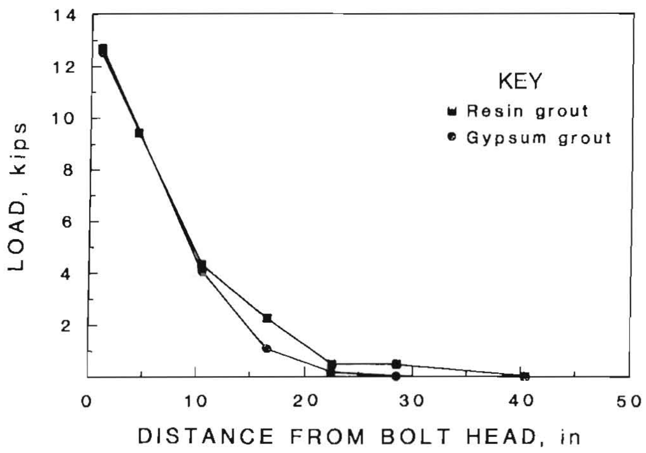

FIGURE 13.—Comparison of grout types.

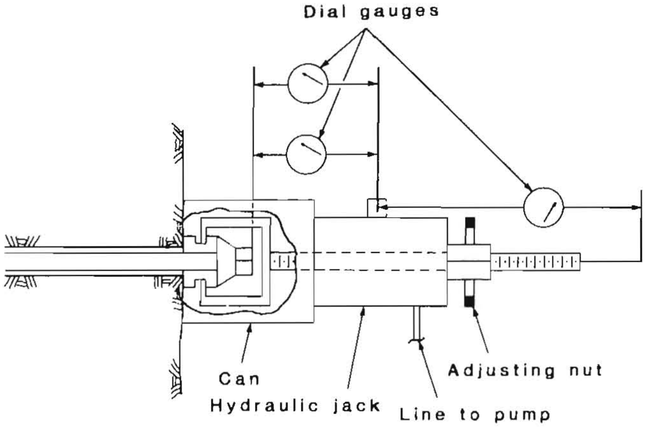

FIGURE 15.—Testing apparatus to determine pull-gear deflections.

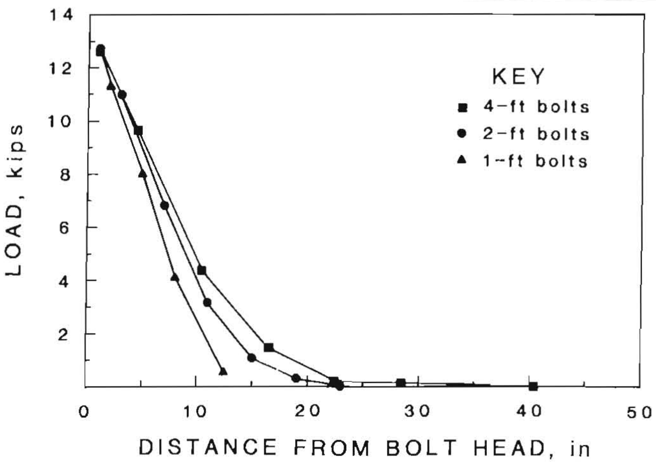

FIGURE 14.—Comparison of bolt length.

Several tests were conducted to determine the amount of measured deflection due to the pull gear. A least squares regression analysis was performed on the data, and a load-deflection relationship for the pull gear was determined. The forged heads on the bolts can cause some misalignment of the pull gear to the pull collar. Therefore, these tests took this misalignment into consideration (fig. 15). The results showed that over half of the deflection measured in a typical test is due to elastic deformation of the pull gear.

Another source of deflection is the mating among the crow's foot, the pull collar, and the bolthead. An adjusting nut (fig. 10) is used to tighten the crow's foot against the pull collar. This adjustment significantly affects the size of the deflections. The intercept value derived from a regression analysis on the experimental data will encompass most of this effect.

Corrections to the experimental results were made to account for the deflection of the pull gear and the seating at the bolthead. The formula is

$$CD = (SP-SD)P-B,$$

where CD = corrected deflection, in,

SP = load-deflection slope of the pull gear, lb/in,

SD = load-deflection slope of the experimental data, lb/in,

B = intercept of the experimental data, in,

and P = load applied to the pull apparatus, lbf.

The parameter B is obtained from the linear statistical fit of the experimental data and represents the effect of seating in the pull gear. The standard deviations of the reduced data (table 3) are significantly lower, indicating that this adjustment is beneficial. However,

TABLE 3. - Experimental bolt deflections

| Bolt length | Deflection at maximum load, in | | | |
|---|---|---|---|---|
| | Raw data | | Reduced data | |
| | Mean | Std dev | Mean | Std dev |
| 4 ft..... | 0.045 | 0.010 | 0.017 | 0.007 |
| 2 ft..... | .040 | .006 | .012 | .004 |
| 1 ft..... | .038 | .005 | .010 | .002 |

parameter B does not fully represent the effect of the adjusting nut. This is apparent because the deflection of the 4-ft bolts is greater than the deflection of the 2-ft and the 1-ft bolts, which were tested when this problem was understood. The 4-ft bolts should have deflection readings less than or equal to those of 2-ft and 1-ft bolts.

The data indicate that the deflection at the maximum load was approximately 0.010 in at the bolthead when the deflections caused by the pull gear and the seating are accounted for. Using this reduced deflection, the FEM grout modulus must still be reduced by a factor of approximately 100, or the rock modulus must be reduced by a factor of approximately 10. Assuming that the additional deflection is taking place at the bolt-grout and the grout-rock interfaces, a different model should be used.

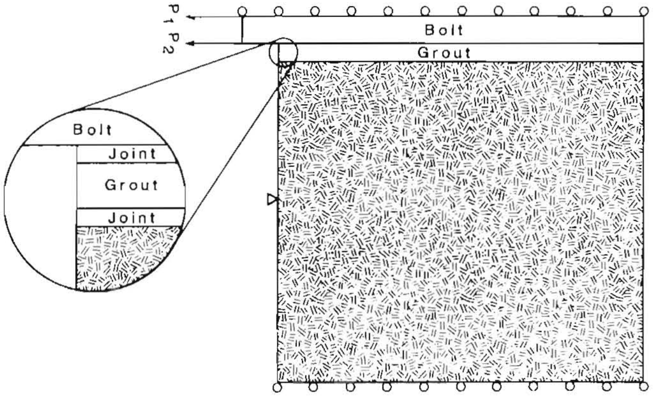

FIGURE 16.—Finite-element model using slip planes.

Therefore, a finite-element model was created with a slip plane between the bolt-grout and the grout-rock interfaces (fig. 16). The shear moduli of these interfaces were varied to match the experimental deflections. The load-transfer rate obtained with this module exactly equals that of the FEM with slip planes, but it uses the proper modulus of the grout and the rock (table 4).

The experimental data from all 4-ft bolts were subjected to an exponential statistical analysis to obtain the coefficient for the following equation:

$$\sigma = \sigma_0 e^{-\alpha y}.$$

TABLE 4. - Modulus comparisons of finite-element model

| | Steel | | Concrete | | Grout | |
|---|---|---|---|---|---|---|
| | Young's modulus (E), $10^6$ psi | Poisson's ratio ($\nu$) | Young's modulus (E), $10^6$ psi | Poisson's ratio ($\nu$) | Young's modulus (E), $10^6$ psi | Poisson's ratio ($\nu$) |
| Experimental values..... | 29 | 0.3 | 3 | 0.2 | 2.1 | 0.25 |
| FEM at 0.10 in of deflection: | | | | | | |
| No joint element...... | 29 | .3 | 3 | .2 | .0188 | .25 |
| With joint element[1]... | 29 | .3 | 3 | .2 | 2.1 | .25 |

[1] The joint properties at 0.010 in deflection are--
G = 120,000 psi = shear modulus of the joint,
Co = 600 psi = cohesion of the joint.

The results are shown in table 5. The value of alpha is the dependent variable. The value for the deflection was obtained by substituting for alpha in the formula

$$\alpha = 4p/V \pi Ed^2$$

and solving for the deflection. This deflection confirms the reduced experimental value of 0.010 in. The index of determination is a statistical measure of the accuracy of the fit.

TABLE 5. - Results from exponential fit of data from laboratory tests of 4-ft bolts

| | |
|---|---|
| Alpha (α), per in................ | 0.1039 |
| Deflection in.................... | .0986 |
| Index of determination........... | .988 |

## DISCUSSION

The FEM does not give an exact fit to the experimental results (fig. 12) even if the deflection of the pull gear is considered. This may be due to several factors. First, the FEM does not represent the true cross-sectional area of the bolt. The area produced by an axisymmetric element is round, but the actual area is not (fig. 7) because of the slots created for the lead wires. However, the bolt diameter must be retained in the FEM so that the shear stresses are represented accurately. Second, high shear stresses are produced in the grout near the applied load. The FEM analysis indicates that the shear stress in the grout is approximately 550 psi, close to the ultimate shear strength. It is possible that fracture of the grout near the applied load is allowing additional deflection. If this were incorporated into the model, the agreement between the FEM and the experimental results might be closer. Third, the FEM does not explicitly model either the ribs on the bolt or the irregularities in the hole.

It is neither practical nor economical to globally model a fully grouted bolt in the same detail as in this study. However, a numerical model of a fully grouted bolt can be made to reflect the load-deflection characteristics of the discrete bolt model. To be effective, the model must simulate both the nonlinear response and the elastic response of the bolt. It must also be able to model the failure of any material (bolt, grout, or rock) at any location of the structural system, including the grout-rock or grout-bolt interfaces. The development of this numerical model would improve the finite-element method as a tool to design the spacing and the appropriate bolt length for roof control systems in coal mines.

Several factors indicate that the transfer of load between the bolt, the grout, and the rock appears to be controlled by mechanical interlock. This conclusion is supported by both experimental observations and FEM results. The FEM results indicate that there is additional deflection at the grout interfaces. In addition, the deflection in the experimental pull tests was totally recoverable, thus eliminating friction as the vehicle of load transfer. Also, when bolts were broken out of the test blocks, there were no signs of chemical adhesion. As seen in figure 11, the stiffness of the bolting system increases as the load on the bolt increases.

Pull tests are routinely performed on fully grouted bolts in underground coal mines for anchorage evaluation. However, the results of these tests may not properly indicate the capabilities of fully grouted bolts. This study has found that the applied load is transferred out of the bolt and into the rock within 22 in (provided that the rock is competent). Therefore, only the lower portion of the installed bolt is evaluated by a typical pull test. It is possible that, because of poor anchorage in the upper half of the bolt, a pull test could show an adequate bolt installation but the roof could still fail. Consequently, pull tests are inadequate to correctly evaluate the support capacity of a fully grouted bolting system.

Bureau of Mines personnel at the Spokane Research Center are continuing to study the plastic and time-dependent characteristics of fully grouted bolts. Inclusion of nonlinear effects in the FEM will improve understanding of the support capacity of fully grouted bolts and also improve numerical modeling techniques in the post-elastic regime.

## CONCLUSIONS

Results from 48 pull tests performed on instrumented, fully grouted bolts showed that hole size and grout type did not have a large influence on the elastic load-transfer rates. Load is transferred from the bolt to the rock via the grout by mechanical interlock between the irregularities in the interfaces. The degree and extent of interlock may be important in determining the anchorage length. The anchorage length was found to extend approximately 22 in from the bolthead for the 4-ft and 2-ft bolts. Consequently, pull tests are inadequate to correctly evaluate the support capacity of a fully grouted bolting system.

An FEM of a grouted bolt was compared to the results of the laboratory tests. If the experimental values for the material properties are used in the FEM, then the deflection and the stress distributions do not match the experimental results. However, if the additional deflection is caused by movement along the grout-rock and the bolt-grout interfaces, then a slip element can be introduced in the FEM to simulate this effect. The FEM could possibly be further refined by the introduction of shear failure criteria for the grout. The load-deflection characteristics of the model for a discrete bolt could be used to develop a numerical model of a grouted bolt suitable for use in a global model of a mine. The numerical model would improve the techniques for designing bolt spacing and choosing bolt length for roof support systems in mines.

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## APPENDIX.--PULL-TEST DATA

| Test | Grout | Hole size, in |
|---|---|---|
| 4-ft BOLTS | | |
| 1 | wc=0.32 | 1 |
| 2 | wc=0.40 | 1-3/8 |
| 3 | wc=0.40 | 1 |
| 4 | wc=0.34 | 1 |
| 5 | Resin[2] | 1 |
| 6 | ...do | 1 |
| 7 | wc=0.34 | 1-3/8 |
| 8 | wc=0.34 | 1 |
| 9 | wc=0.34 | 1-3/8 |
| 10 | wc=0.30 | 1-3/8 |
| 11 | wc=0.30 | 1 |
| 12 | wc=0.40 | 1 |
| 13 | wc-0.34 | 1 |
| 14 | wc=0.34 | 1-3/8 |
| 15 | Resin | 1 |
| 16 | Old resin | 1 |
| 17 | Water capsules[3] | 1 |
| 18 | Resin | 1 |
| 19 | ...do | 1-3/8 |
| 20 | ...do | 1 |
| 21 | Overspin[4] | 1 |
| 22 | Water capsules | 1 |
| 23 | ...do | 1 |
| 24 | Underspin[4] | 1 |
| 25 | Water capsules | 1 |
| 4-ft BOLTS--Continued | | |
| 26 | Water capsules | 1 |
| 27 | ...do | 1 |
| 28 | wc=0.34 | 1 |
| 29 | Resin | 1 |
| 2-ft BOLTS | | |
| 1 | wc=0.32 | 1-3/8 |
| 2 | wc=0.4 | 1-3/8 |
| 3 | wc=0.34 | 1 |
| 4 | wc=0.4 | 1 |
| 5 | wc=0.34 | 1-3/8 |
| 6 | wc=0.32 | 1 |
| 7 | Resin | 1 |
| 8 | ...do | 1 |
| 9 | ...do | 1 |
| 1-ft BOLTS | | |
| 1 | wc-0.34 | 1-3/8 |
| 2 | wc=0.34 | 1 |
| 3 | wc-0.32 | 1 |
| 4 | wc=0.40 | 1 |
| 5 | wc=0.40 | 1-3/8 |
| 6 | wc=0.32 | 1-3/8 |
| 7 | Resin | 1 |
| 8 | wc=0.34 | 1 |
| 9 | Resin | 1 |
| 10 | ...do | 1 |

[1] WC = water-cement ratio of slurry gypsum grout.

[2] Polyester resin.

[3] Gypsum grout using water capsules.

[4] Spin time variations of polyester resin.

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