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Transfer Mechanics of Full-Column Resin-Grouted Roof Bolts

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UNITED STATES DEPARTMENT OF THE INTERIOR
Manuel Lujan, Jr., Secretary

BUREAU OF MINES
T S Ary, Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	lb/in	pound per inch
in	inch	pct	percent
in^2	square inch	psi	pound (force) per square inch
lb	pound	s	second
lbf	pound (force)		

TRANSFER MECHANICS OF FULL-COLUMN RESIN-GROUTED ROOF BOLTS

By Stephen C. Tadolini[1] and Robert C. Dyni[2]

ABSTRACT

The U.S. Bureau of Mines conducted a laboratory investigation designed to evaluate the stress and deformation characteristics of fully grouted roof bolts subjected to various magnitudes of end loadings. The experiment and subsequent analysis were completed, utilizing axial deformation data obtained ultrasonically from forty-one 4-ft, grade 40 roof bolts, with a total of 132 measurement locations along the lengths of the bolts. The ultrasonic measurement instrumentation used in this investigation allowed for elongation measurements without requiring extensive bolt modifications.

The results indicate that approximately 39 pct of the applied end load dissipated within the first 3.4 in of the bolts. However, only 3 pct of the applied load was realized beyond 28 in of the grout column.

Data are presented individually for every 6-in increment of bolt length, and analysis was performed using statistical, nonlinear equations developed for 5,000 and 8,000 lb loading conditions.

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INTRODUCTION

Millions of roof bolts are used each year to provide structural support in underground U.S. metal, nonmetal, and coal mines. An increasing percentage of these bolting systems are utilizing resin-anchor and resin-assisted mechanical anchor combination bolts, as well as mechanical point anchor bolts.

The method by which point expansion anchor bolting systems carry roof loads is well understood and documented (*1*).[3] However, the mechanisms by which resin-grouted bolting systems carry roof loads is much less understood, mainly because testing procedures used to evaluate point anchor systems are not entirely valid for resin-grouted bolts.

Significant advances in the areas of mine design and strata characterization utilizing analytical, empirical, and observational methods have been made during the last 10 years. The advances necessitate the requirement for innovative strata stabilization and control utilizing various types of bolting systems. Innovative mine design practices require unique strata control to optimize extraction and ensure safety for underground personnel. Currently, the bolting patterns and configurations utilized for strata control are based upon past practice and on trial and error experiments. Although recent advances in numerical modeling have provided mine planners with a powerful tool to assist with mine design, this technique is still inadequate to design bolting patterns using resin-grouted bolts (*2*). The mechanics and relationships between the applied loads and the interaction between the grouted bolt system (bolt, grout, and surrounding material) have not been defined and verified.

Previous research has shown the full-column resin-grouted bolts rely on the mechanical interlock of the resin interstices within the borehole wall and along the surfaces of the reinforcement rod to secure the surfaces together (*2*). The anchorage levels associated with typical fully grouted bolts are extremely high and can exceed the tensile strength of the bolt. The reported distribution of anchorage along the bolt axis has been estimated to range from 1,500 to 4,000 lb/in, depending on the diameter of the bolting system used and the strength of the strata in which it is installed (*3*).

To more fully understand the load transfer mechanics associated with resin-grouted bolting systems so that optimum grout column lengths for maximum load dissipation characteristics can be determined, the U.S. Bureau of Mines conducted an investigation designed to evaluate the behavior of full-column, resin-grouted bolts subjected to a range of end-loading forces. Previous Bureau research projects investigated the influence of installation procedures on the effectiveness of resin-grouted roof bolts (*4-5*). The results of these past laboratory and field investigations illustrated the necessity for investigating the nonlinear behavior of the stress distribution in fully grouted bolts.

This investigation consisted of installing 41 full-column resin-anchor roof bolts into two concrete blocks, then determining the resulting stresses and deformations induced on the bolts as they were subjected to a range of tensile loads applied at the boltheads. This method of loading has been shown to be typical of the actual loading process of resin-grouted bolting systems (*6*). In fully grouted passive support systems, roof movements generate vertical load on the bearing plate and subsequently loads on the bolt. The stress and deformation calculations were determined by using a recent technology development. A prototype ultrasonic measurement system, developed through Bureau research, was used for this investigation; this instrumentation is capable of determining axial deformation of a bolt between the bolthead and any location within the bolt. With this system, no significant physical modifications of the bolts were necessary to accommodate strain gages or vibrating wires for axial deformation measurements. Such modifications can create zones of induced stress concentrations; these stress concentrations can produce erroneous test results, particularly at low stress levels. By measuring the axial deformation of a bolt throughout its length, calculations could be made to determine the amount of load induced at these locations by the applied end-loading conditions.

The results of this investigation provide a more comprehensive understanding of the load transfer mechanisms associated with fully grouted roof bolting systems, and provide a basis on which to choose adequate column lengths for maximum load dissipation characteristics. These parameters become extremely important as innovative support designs using new combination systems with partial grout columns are being introduced into the mining industry.

[3] Italic numbers in parentheses refer to items in the list of references at the end of this report.

INSTRUMENT DESCRIPTION

The success of the laboratory investigation depended largely on the use of ultrasonic instrumentation to measure deformation of the test bolts with a high degree of precision and accuracy. The repeatability of the instrument has been previously determined (*7*); an instrument resolution of 0.0001 in, or ±150 lb, has been realized.

Since the bolts being analyzed required much less physical alteration than traditional strain-gaged bolts, the decision to use ultrasonic technology seemed to be a logical one.

THEORY OF OPERATION

The ultrasonic instrument used in the laboratory investigation was the Raymond[4] PDX-934 Bolt Gage (fig. 1). The instrument transmits an ultrasonic wave through a bolt via a signal transmitter-receiver transducer magnetically attached to the bolthead (fig. 2). This sound wave is reflected from the far end of the bolt or from a small diameter reflector hole drilled orthogonally to the bolt axis at any location within the bolt length, and is returned to the signal transducer. The instrument determines the amount of time it took for this sound wave to travel to the end of the bolt and back. By comparing this result with the round-trip travel time in the same bolt under stress, the change in length can be determined. This travel time is affected by bolt stress and strain, and changes linearly with respect to bolt loads. The sound waves are introduced in the bolt by a piezoelectric transducer, which also detects the return sound waves that have been reflected from the end of the bolt or other established reflectors. The instrument's microprocessor converts these time measurements to a change-in-length reading viewed on the front display panel. The instrument calculates the length values by Hooke's law, which assumes that the material being tested remains linearly elastic. Once a relationship between round-trip travel time increase and elongation has been determined for a particular production lot of bolts, the instrument can be programmed with this calibration factor and is then ready to display change in length of each bolt in the lot for any applied loading condition (*8*).

INSTRUMENT OPERATION

The following procedure was used for testing the bolts in the laboratory investigation. First, the calibration factor described in the previous section was determined and entered into the instrument. Once the calibration factor was determined, the instrument was ready for analysis of all bolts in the test. Second, a light coating of molybdenum grease was applied to the head of the bolt being tested; this grease provided a good conductive contact for the transducer-bolt interface. After adjusting the instrument gain values to reflect properly the signal off the desired location in the bolt, the bolt was ready for analysis.

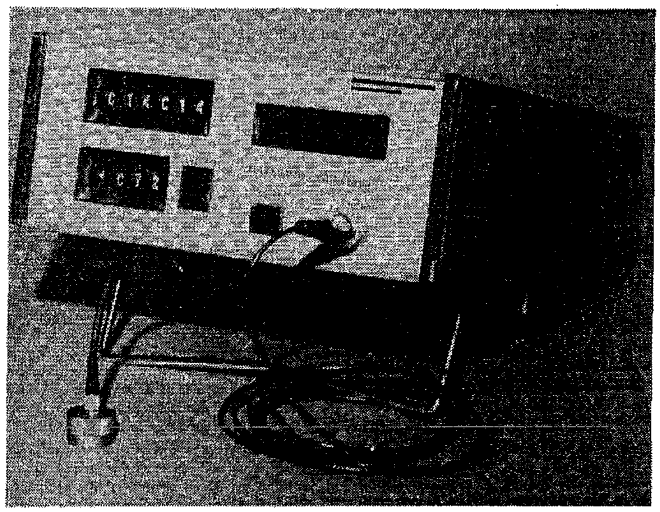

Figure 1.—Raymond bolt gage.

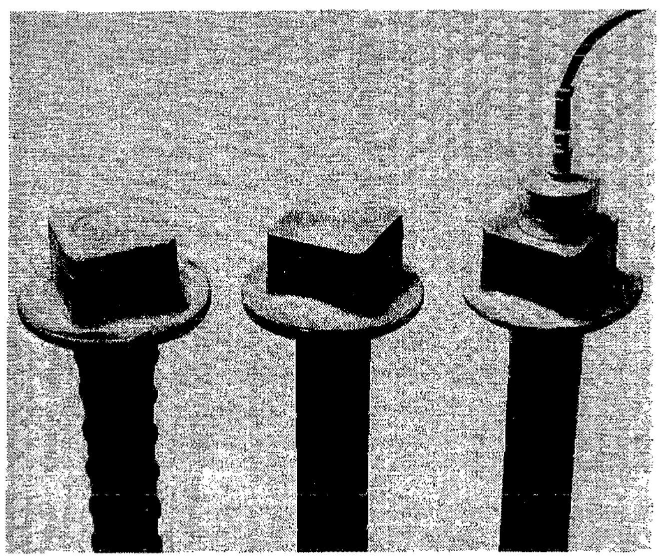

Figure 2.—Unsurfaced bolthead, surfaced bolthead, and surfaced bolthead with transducer attached.

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

PREPARATION OF LABORATORY INVESTIGATION

Preparation of the investigation required two separate tasks. First, two concrete blocks were constructed to accommodate the bolts being tested. The second task involved preparing the bolts for analysis.

The investigation required that the overall elongation of each bolt and the elongation of intermediate points within each bolt be determined for every loading condition so that an accurate determination of loads and stresses could be determined for each bolt. Therefore, small diameter holes were drilled into each bolt at various locations along its length to provide additional reflector locations for the ultrasonic signal. The instrument was capable of delineating between reflector locations by adjusting to the strength of the propagating sound wave.

BOLT PREPARATION

Machining

The bolts modified for testing were grade 40, No. 6 rebar, polyester resin-type roof bolts. Since bolt manufacturers stamp bolt specifications on each bolthead, each head was to be lathed smooth to accommodate the ultrasonic signal transducer (fig. 2). The foot of each bolt was also lathed smooth to minimize test signal interference and to provide an additional reflecting surface for the instrumentation.

Drilling

Each bolt had three holes drilled orthogonal to the bolt axis at various locations along its length. Table 1 shows the spacing pattern used for each bolt. The holes were drilled with a high-speed drill and jig assembly (fig. 3) and had a diameter of 0.04 in. Previous tests (*9*) indicated that this hole diameter does not affect the material properties or strength of the bolts. The spacing pattern assured that every section of roof bolt length was adequately represented.

Calibrating

The bolts were calibrated with the ultrasonic instrument to obtain baseline length data before being installed in the three test blocks. Since all the bolts came from the same production lot, it was assumed that all the bolts would exhibit the same material behavior.

A standardized bolt that represented the material properties of the entire lot of test bolts was prepared to determine the necessary signal velocity properties required for input into the ultrasonic instrument's microprocessor. Additionally, the modulus of elasticity, E, was determined for the steel by selecting five additional bolts from the lot and loading them in a press while measuring the corresponding elongation values.

The preparation of the standardized bolt, used for material velocity determinations, consisted of cutting the bolt to a known length; this length was determined by micrometer measurements with an accuracy exceeding that of the ultrasonic instrument. The velocity of the material could then be determined, and a calibration factor then formulated.

The effective area was also determined from these same roof bolts. The value for the elasticity was determined to be approximately 29.4×10^6 psi. The average value for the effective area was 0.442 in^2. These values obtained from the standardized bolt were used for the calculations for the bolts installed in the three test blocks.

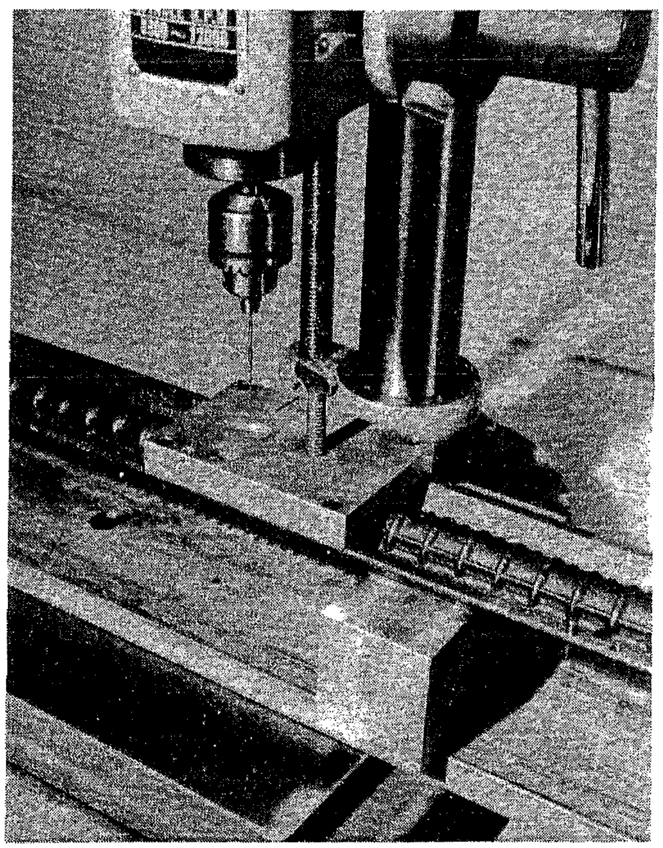

Figure 3.—Bolt drilling assembly.

Table 1.—Location of reflector holes in test bolts

Bolt ..	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
2[1] ...	X	X	X	X	X																								
3						X	X	X	X	X																			
4											X	X	X	X															
5	X																												
6		X													X	X	X												
7			X			X																							X
8				X			X											X	X	X									
9	X				X			X			X																		
10 ...									X			X									X	X	X						
11 ...		X								X			X		X														
12 ...						X								X										X	X	X	X	X	
13 ...			X													X													X
14 ...							X																						
15 ...				X							X						X	X											
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32 ...																						X							
35 ...																								X					
37 ...																							X						
39 ...																									X				
43 ...																										X			
47 ...																											X		
48 ...																												X	

	30	31	32	33	34	35	36	37	38	39	40	41
6				X			X					
7	X	X	X		X	X		X	X	X	X	X
12 ...				X	X	X	X					X
13 ...	X	X	X					X	X	X	X	
18 ...								X				X
19 ...	X	X	X	X	X	X		X	X	X	X	
24 ...				X	X		X					
25 ...	X	X	X			X		X	X	X	X	X
31 ...	X		X	X					X			X

[1]Distance, in inches, from bolthead.

BLOCK PREPARATION

Construction

The three test blocks were constructed of monolithically poured concrete. Both blocks had dimensions of 3 by 3 by 5 ft (fig. 4). The concrete was allowed to cure for approximately 2 weeks before bolt-hole drilling began to ensure sufficient concrete strength. The concrete was also poured into preconstructed sample boxes to permit the drilling of NX-size core samples (2.125-in diam) for physical property testing. The samples were stored under the same temperature and humidity conditions as the test blocks to ensure that the calculated physical properties would be representative of the test block material. The samples were tested at the same time; the testing was performed on the bolts.

Fourteen samples were tested at four different confining pressures to permit the development of load deformation curves and Mohr's envelopes. The values obtained from the data include compressive strength, modulus of elasticity, and shear strength. The four selected confining pressures were 0, 500, 1,000, and 1,500 psi. The cores were prepared, tested, and analyzed in accordance to the American Society for Testing and Materials (ASTM) standards (*10*). The average compressive strength, converted to a 1:1 ratio of diameter to length, was 4,620 psi. The average tangent modulus of elasticity, calculated at 50 pct of the ultimate strength, was 2.28×10^6 psi. The shear strength for the material, determined from 11 samples, was 1,211 psi with an angle of internal friction of 33.3°.

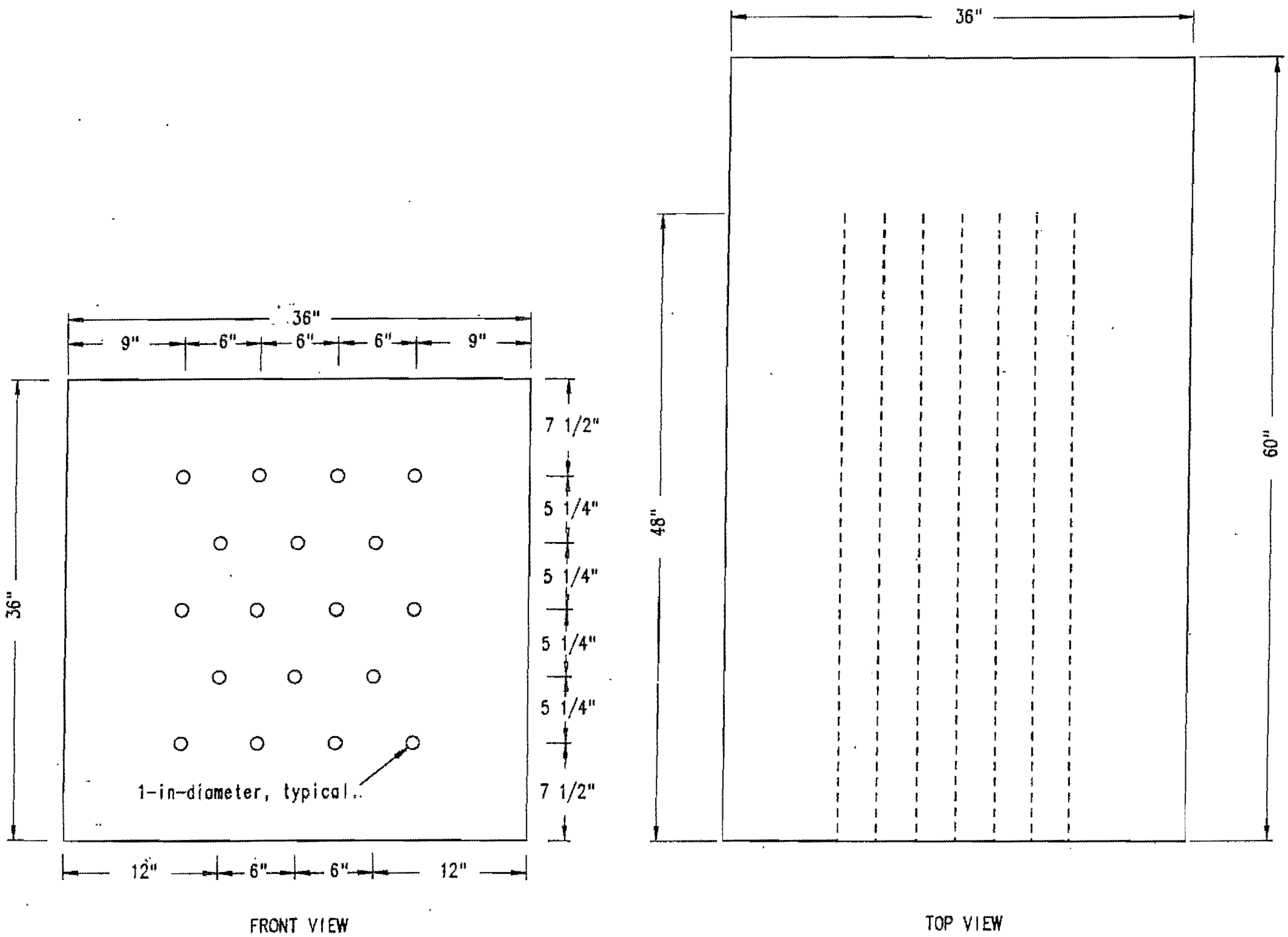

Figure 4.—Concrete block construction details.

Drilling

The bolthole pattern used for both test blocks is shown in figure 4. The holes were all drilled, with a diamond tipped masonry bit, to the manufacturer's suggested dimensions. The specifications suggest a final finished hole diameter of 1 in and a final hole length 1 in longer than the tendon. The holes were examined with a holometer, which measures the finished diameter of the hole. A minimum hole separation of 6 in was required due to the size of the bolt-pulling apparatus. A minimum distance of approximately 8 in was used for separation between the outer boltholes and the edge of the blocks. Previous Bureau studies have shown if the separation between the bolts and the edge of the concrete blocks is too small, cracking of the blocks along their edges can occur during pull testing.

Bolt Installation

The resin grout used for bolt installation was a two part, single tube, 60 s spin time, 48 in equivalent resin-type.

The bolt installation equipment included a handheld, pneumatic rotary bolting drill attached to a 10-ton[5] forklift. The bolts were installed horizontally so that the forklift could be used to drive the bolts into the holes.

To install the bolts into the test blocks, a bolt and its corresponding bolthole were first prepared for installation. This included sliding a pull collar onto the bolt, and inserting a resin cartridge into the hole (fig. 5). Second, the forklift with the rotary drill attached was positioned in front of the hole (fig. 6). Third, the bolt was forced into the hole by driving the forklift forward, and at the same time, the bolt was spun with the rotary drill to begin mixing the resin. After the bolt was emplaced and spun for approximately 60 s, the bolt continued to be held in place for approximately 30 s until the resin was completely cured. The forklift was then retreated. Visual examinations ensured the bolts were fully encapsulated in the grout. This procedure was repeated for all bolts in both blocks. The bolts were allowed to cure for 1 week prior to testing to ensure maximum anchorage capacity (*11*).

[5]In this report, "ton" indicates 2,000 lbf.

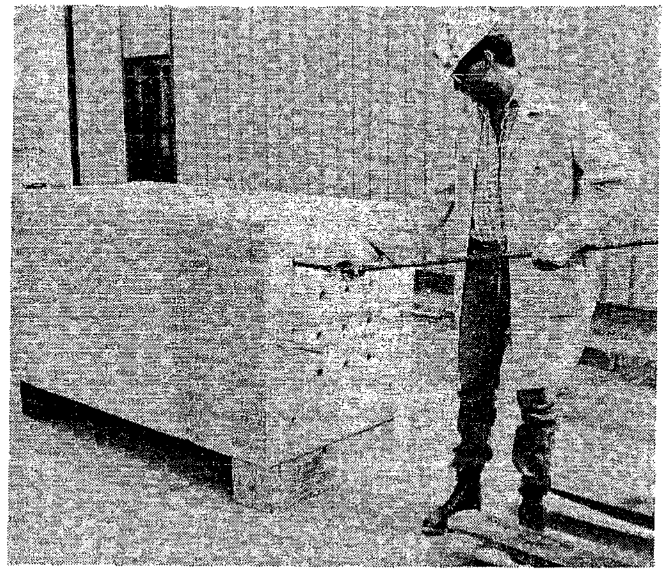

Figure 5.—Preparation of test bolt for installation into concrete block.

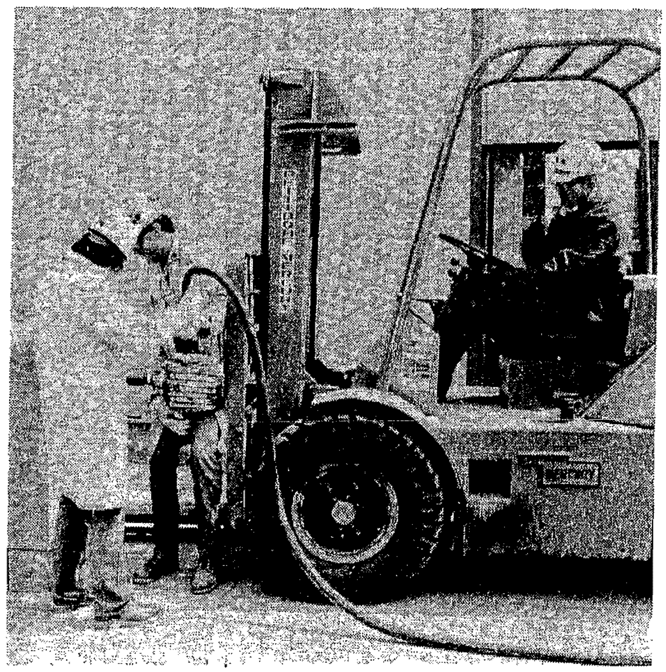

Figure 6.—Installation of test bolt into concrete block.

DATA

The data obtained from the test apparatus were in the form of elongation measurements obtained from the ultrasonic instrument and load readings taken from the calibrated gage attached to the hydraulic pull-test apparatus.

ACQUISITION AND REDUCTION

The data were obtained by direct readings from the ultrasonic instrument and the load indicator (fig. 7). Each bolt reflector location was individually monitored, while load was applied. The load was applied to each bolt from 1,000 to 8,000 lb in 1,000-lb increments; the loads were monitored by using the calibrated pressure gage attached to the hydraulic ram assembly. At each load level, an elongation reading of a particular reflector location was taken with the ultrasonic instrument. This provided the change in length of a reflector location with respect to the transducer location induced by a given applied load. The data obtained in the lab were transferred to a computer file for reduction, graphic display, and subsequent analysis.

ANALYSIS TECHNIQUE

The ultrasonic instrument can be considered an electronic strain gage. Any strain gage, whether mechanical, electrical, optical, or some other type, does not actually measure strain. Strain gages are deformation sensitive; that is, they are able to respond to deformation, such as in this case, or a change in a finite length. Therefore the measured quantity obtained from the strain gage or the ultrasonic instrument is proportional to an average strain in the gage length of the examined sections. In regions of a high-strain gradient, an average reading of strain may be appreciably less than the maximum occurring at another point along the length of the bolt. This difficulty has been partially overcome by examining small gage lengths of the bolt, but there is a physical limitation on the size of the smallest gage length that can be practically considered. The elongation data for this investigation, which indicated the change in length of the distance between reflector locations and the boltheads for each applied loading condition, are considered strain averages for specific sections of the bolt for each applied loading condition. To assist in the evaluation, the data were assembled into a series of graphs. Forty-one bolts, with 132 total reflection points, were tested to provide the input data for analysis.

Phase I Analysis

The analysis of the data included three separate phases. Phase I involved plotting the values obtained for each pull test. The plots, illustrating reflector displacement for each loading condition, were completed for each of the 41 bolts. A typical data representation for a bolt with five reflector signals at the indicated locations is shown in figure 8. In this figure, the displacements occurring at approximately the 21- and 27-in lengths are essentially the same values, indicating that little or no displacement has occurred

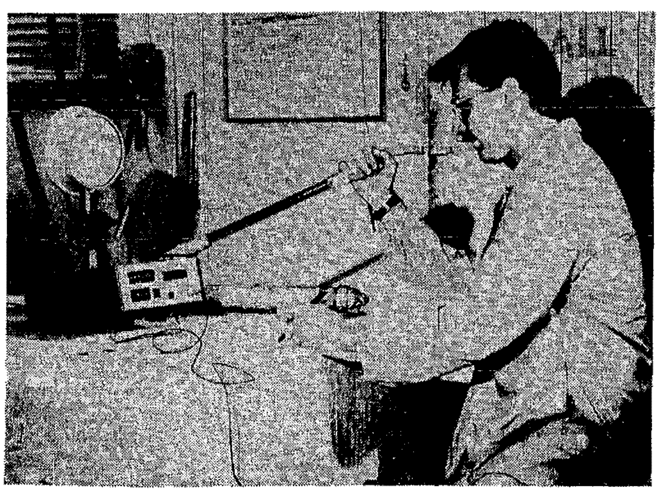

Figure 7.—Bolt testing assembly including bolt gage, and hydraulic ram with pressure dial.

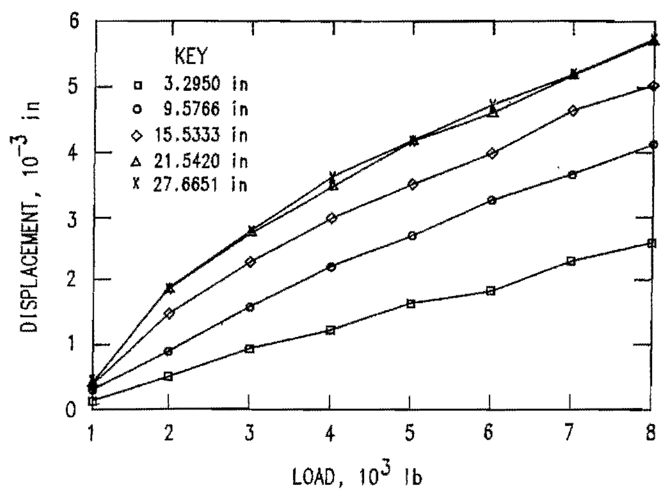

Figure 8.—Typical data representation for bolt with five reflector signals.

between the 21- and 27-in levels. These displacements were determined by measuring the distance between each reflector and the bolthead at each loading increment; the distance is the midpoint for the analyzed section.

To analyze the individual amount of displacement that occurred in each section of the bolt, the values were normalized by subtracting the elongations that had occurred up to that point. The results (fig. 9) provided the actual displacement that occurred in each section of the bolt. It is apparent that little or no displacement occurred at the 27-in level of this bolt, even at a load of 8,000 lb.

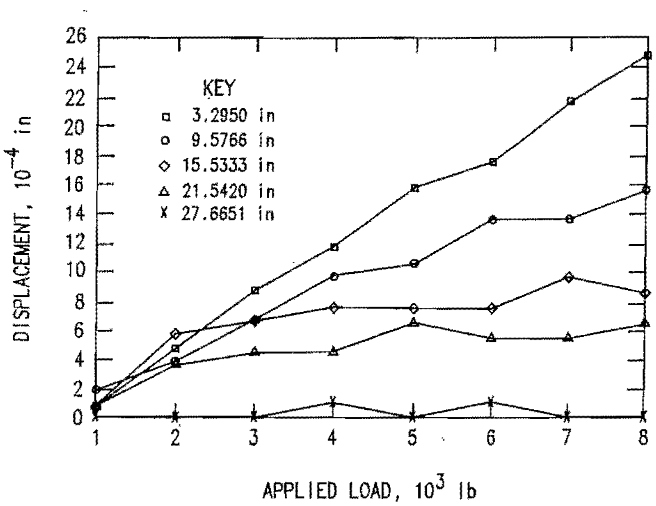

Figure 9.—Actual displacements occurring in each bolt section.

Phase II Analysis

Phase II of the data analysis involved calculating the loads from the measured displacements for each loading increment. Hooke's law was used for these calculations (equation 1). (The assumption required for utilizing Hooke's law for these calculations is that the bolts remain linearly elastic under load.)

$$\delta = \frac{PL}{AE}, \tag{1}$$

where P = calculated average load, lb,

L = length between reflector location and transducer location, in,

A = cross-sectional area, in^2,

E = modulus of elasticity of bolt steel, psi,

and δ = measured displacement, in.

The equation was rewritten to calculate the measured average load at each reflector signal to:

$$P = \frac{\delta AE}{L}. \tag{2}$$

The plot shown in figure 10, utilizing the displacement data calculated and shown in figure 9, illustrates the relationship between calculated average loads and applied loads for each loading condition. The plot depicts how rapidly the loads are dissipated from the bolt back into the surrounding material. These values were calculated for every reflector signal at each data location.

To assist further in the analysis, plots were developed to analyze the relationships between the displacement (δ) and the length (L) along the bolt at which they occurred.

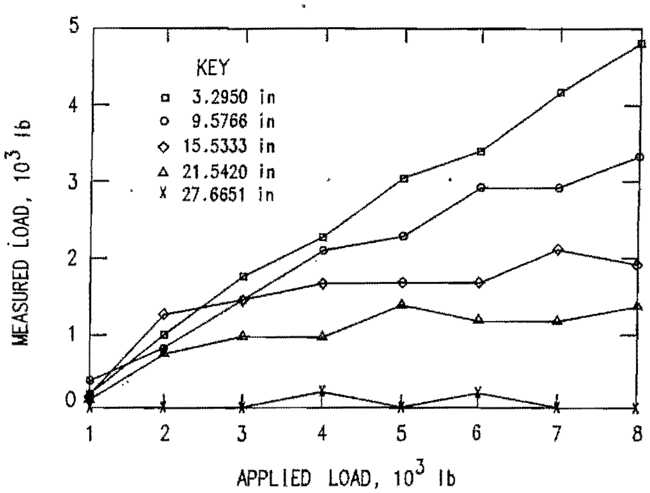

Figure 10.—Measured loads calculated at each loading condition.

The data obtained for 5,000 lb of applied load (fig. 11) were combined from all the tests and fit to a curve.

$$Y = A + B^{*}LOG(X), \tag{3}$$

where Y = the displacement, in,

X = the distance along the bolt axis, in,

A = 4.4788×10^{-4},

and B = 1.0217×10^{-3}.

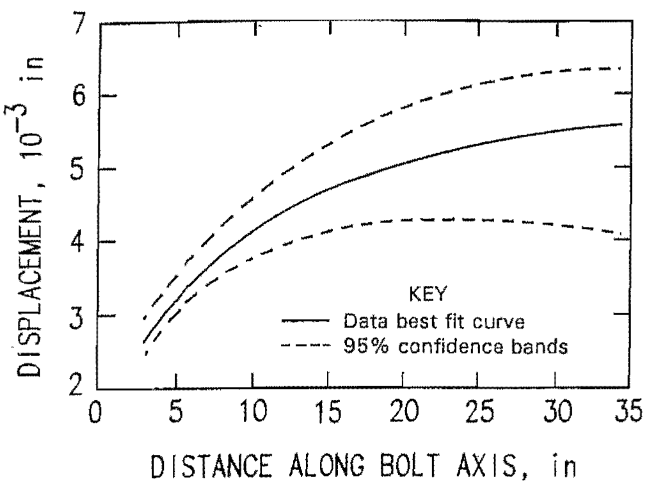

Figure 11.—Calculated displacements determined along bolt axis at 5,000 lb applied axial load.

The coefficient of correlation (R^2) for this equation is 0.747, which is thought acceptable for this large data sample. By taking the first derivative of equation (3) with respect to the distance X, the slope of the line is

$$\frac{d\delta}{dL} \text{ or } \frac{d\delta}{dX}.$$

To obtain the slope of this curve at any distance (L) along the length of the bolt, the result would be B/X. Hooke's law can be rewritten as:

$$P = AE \frac{d\delta}{dx} \text{ at } X = L. \tag{4}$$

The slopes of the data were analyzed by combining the data in 6-in increments. The sections evaluated were 0 to 6, 6 to 12, 12 to 18, 18 to 24, and 24 to 30 in. The data in the first increment, 0 to 6 in, appeared to be linear and were analyzed utilizing simple linear regression techniques (*12*). The data from 132 reflector signal measurements were fit to the linear equation:

$$J = M * K, \tag{5}$$

where K = applied load, lb,

J = measured load, lb,

and M = slope of the line.

The value for M was calculated to be 0.61, and the line was determined to be linear, as evidenced by R^2 of 0.998. The standard error of the J estimate utilizing this relationship was ±67 lb, which is well within the accuracy of the measurement system.

The same technique was applied to reflector signals between the 6- and 12-in level. The value for M was calculated to be 0.44, while R^2 dropped to 0.855, and the standard error of the Y estimate was 210 lb. The technique was applied to the 12- to 18-in, the 18- to 24-in, and the 24- to 30-in sections. The respective slopes were calculated to be 0.25, 0.11, and 0.04, respectively. The decrease in the slope value is an indication of load transfer.

Phase III Analysis

The third phase of the individual bolt analysis involved calculating the loads at each reflector signal location. The average loads were plotted with respect to the bolt axis to illustrate the dissipation of applied load. The series of curves from the 41 tests (fig. 12) show the dissipation of measured load along the bolt axis for each increment of applied load. The load dissipates rapidly between the head of the bolt and approximately the 10-in level. The load dissipates almost completely at a transfer length of 28 in. When the load levels were relatively low, the load dissipation pattern remained consistent. This was noted in several of the applicable cases. Reflector signal locations beyond the 30-in level showed no relative displacements, indicating that the applied load had dissipated completely by the time it had reached that point.

This particular system of resin, concrete, bolt, and installation procedure indicated that complete transfer of applied end load occurred at approximately 28 in along the bolt axis, even at relatively high loads.

EXPERIMENTAL RESULTS

The data were compiled and combined to facilitate presentation into a practical and usable form. To accomplish this, the calculated loads-versus-distance along the bolt axis were analyzed to be presented as a statistical function. The initial analysis included all the bolt reflection locations ranging from 1.9341 to 49.1614 in from the head of the bolts. These were the distances between the bolthead to the first reflector signal and the bolthead to the end of the bolt. The calculated length was the average distance between any two reflectors.

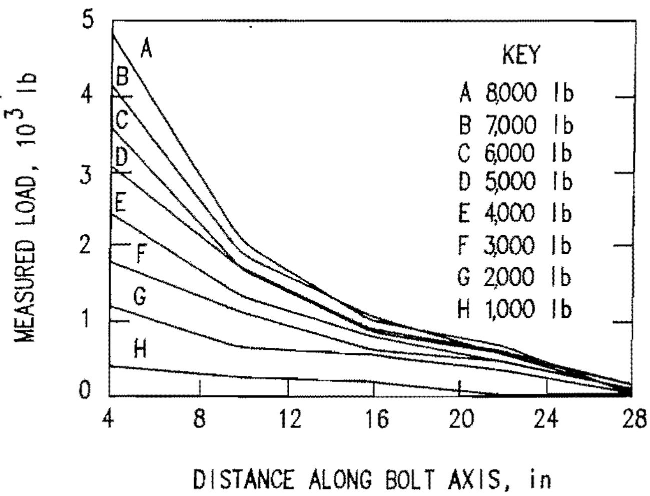

Figure 12.—Combined and averaged dissipation lines for applied load.

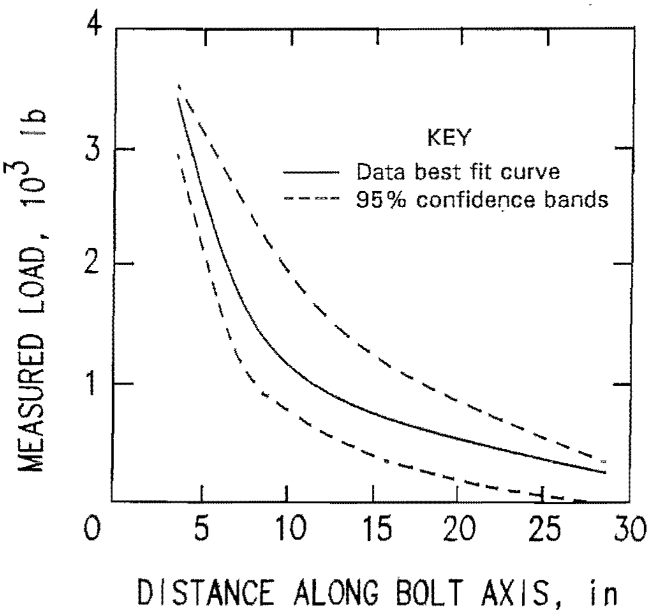

Figure 13.—Statistical curve and confidence interval for 5,000 lb loading increment.

Unfortunately, the statistical analysis was thought inappropriate due to the large amount of fluctuation occurring in the first 13 reflector points or 101 values determined at lengths less than 6 in. The statistical analysis, presented earlier, clearly indicated that this portion of the bolt elongated near linear with respect to anchor loading, which severely influenced the curve-fitting analysis. After the first 6 in of the bolt were examined, it was apparent that the loads applied at the end of the bolt began to dissipate into the rock mass through the resin grout. To accommodate this phenomenon, only the average data obtained from reflector locations greater than 6 in (3-in gage length) from the end of the bolts were used for the statistical analysis. Simple statistical analysis was used to analyze, calculate, and determine best-fit curves (*12*). The results of this analysis are shown for the 5,000 and 8,000 lb loading increments (figs. 13-14). The best-fit equation for the data was in the form

$$Y = A + \frac{B}{X}, \qquad (6)$$

where X = distance along the bolt axis, in,

A and B = constants,

and Y = amount of load that occurs at X.

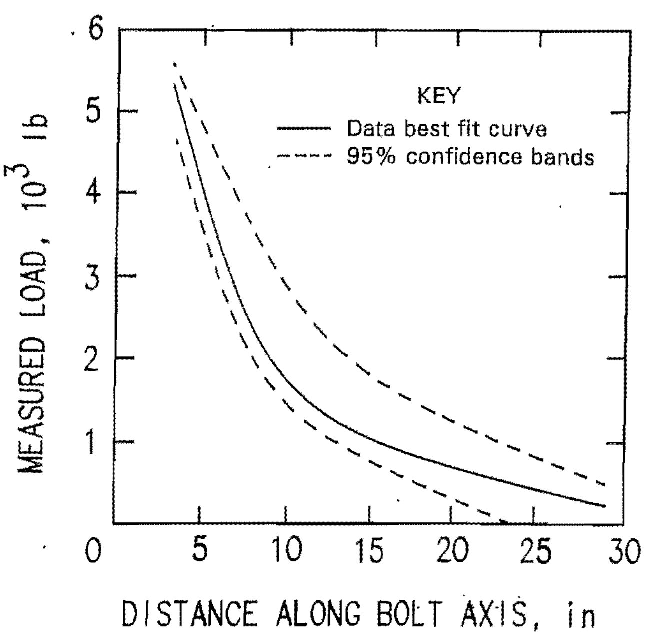

Figure 14.—Statistical curve and confidence interval for 8,000 lb loading increment.

Table 2 contains the values for the constants A and B. The R^2 and the maximum standard deviation between the measured and calculated values for the two presented cases are statistical measurements of the accuracy of the fit.

These values for the 5,000 lb case are $R^2 = 0.908$ and a maximum standard deviation of 952 lb. The values for the 8,000 lb case indicate a value of $R^2 = 0.949$ and a maximum standard deviation of 913 lb. Considering that 119 data points were analyzed for each case, the statistical equations adequately define this transfer phenomenon, and the standard deviations are within the accuracies of the test system and measurement instrumentation.

Table 2.—Statistical constants for regression analysis

	5,000-lbf case	8,000-lbf case
Constant A	-753	-1,391
Constant B	27,302	43,494
Correlation coefficient (R^2) ..	0.926	0.949

GENERAL DISCUSSION

Pull tests are performed on resin-grouted roof bolts in underground mines to determine the ability of the resin and bolt to anchor adequately in the surrounding medium. The distance that this applied load transfers from the bolt and into the rock mass is an essential variable for accurate bolt and grout length design determinations.

In this investigation, the data were merged, utilizing the raw measured average loads calculated from displacements to determine the percentage of applied load that could be anticipated along the length of the bolt axis. To accomplish this, each loading increment from 1,000 to 8,000 lb was considered separately. The data were calculated at 6-in intervals along the bolt axis, starting with the 3-in level and concluding at the 27-in level. The amount of displacements measured beyond the 27-in level were considered negligible. The percent of realized load-versus-applied load is shown in figure 15 for each loading condition. The specific data for each loading increment are provided in table 3.

The averages (table 3) provide a practical method for estimating the amount of load that can be expected along the length of a 3/4-in full-column resin-grouted roof bolt.

The ultrasonic instrumentation provided an accurate measurement of the bolting system stiffness. The system stiffness is defined as the ability of the bolt to resist deformation when subjected to applied load. The experimental setup eliminated the deformations that traditionally occur in standard pull-test apparatus by measuring the elongation values directly from the bolthead. The system stiffness for an ungrouted bolt and fully grouted bolt are shown in figure 16. The data indicate that the stiffness of the 48-in fully grouted bolt system, approximately 1.6 million lb/in, is five times greater than an ungrouted bolt subjected to 8,000 lb of applied load. The system stiffness is an important and often ignored input parameter required to investigate the total system response in numerical models that examine bolt performance.

The resulting equations and the percentage of actual load with respect to bolt length developed from this investigation will be useful in assisting mine operators plan preliminary mine support design. However, the mechanical properties of the bolting material and geologic strata should be considered prior to final design recommendations. The Bureau is continuing to examine the effectiveness of support systems under a wide range of geological conditions. The ultimate goal of these investigations is to provide engineered support designs that will provide safe working areas under diverse and hazardous underground mining conditions.

Table 3.—Percentage value of applied load measured along bolt axis, percent

Distance along bolt axis, in	1,000 lb	2,000 lb	3,000 lb	4,000 lb	5,000 lb	6,000 lb	7,000 lb	8,000 lb	Average
6	46.7	63.6	62.9	63.8	64.3	63.0	62.8	63.2	61.3
12	33.9	42.2	38.8	33.0	30.6	27.2	26.8	25.1	32.2
18	21.5	20.5	16.5	16.4	15.3	12.1	11.1	10.2	15.4
24	9.2	11.8	14.0	11.5	6.8	9.2	6.9	6.1	9.4
30	8.6	4.8	5.4	2.9	1.0	2.9	.7	.9	3.4

NAp Not applicable.

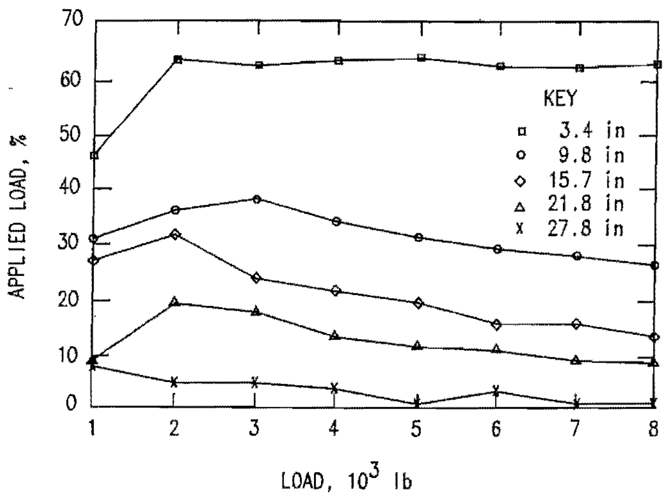

Figure 15.—Percentage of realized load-versus-applied load.

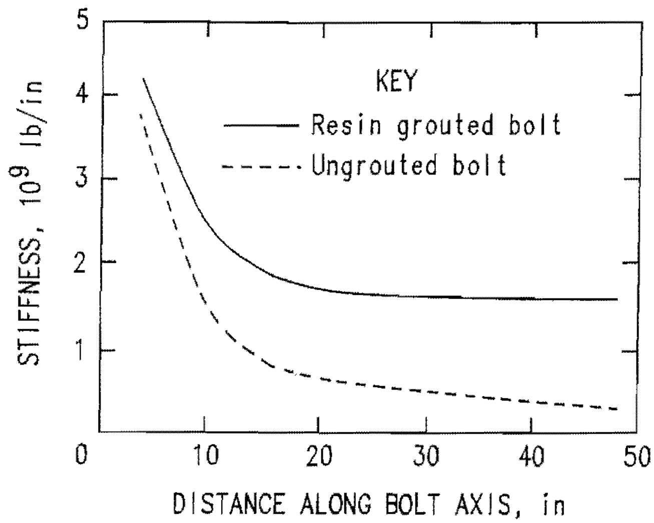

Figure 16.—Bolt stiffness for ungrouted and resin-grouted roof bolt.

CONCLUSIONS

A laboratory investigation designed to evaluate the characteristics of fully grouted roof bolts subjected to various magnitudes of end loadings was performed on forty-one 48-in, grade 40 rebar bolts using ultrasonic measurement technology. The results of the investigation revealed that an average of approximately 39 pct of the applied load dissipated in the first 3.4-in of the bolts. The subsequent two average measurement distances of 9.8 and 15.7 in of the bolt carried average totals of 68 and 85 pct of the applied load, respectively. The portion of the bolt between 15.7 and 21.8 in realized an average of only 9 pct of the applied load. The remaining portion of the bolt underwent only minor displacements, representing approximately 3 pct of the applied load.

The slope of the displacement-versus-load curves were independently calculated for 6-in sections of the bolts. As the distance from the bolthead increased, the slope of the line decreased, which indicates load transfer is occurring. Linear regression analysis techniques were thought inappropriate in describing load dissipations. These conclusions were based on a statistical analysis performed on 132 data locations situated at various distances from the boltheads. Nonlinear equations were formulated for the 5,000 and 8,000 lb loading conditions. These equations represent the nonlinear load dissipation load transfer mechanics beyond the 6-in linear portion.

The use of ultrasonic instrumentation allowed for the nondestructive determination of elongations of the bolts; this method did not require extensive bolt modification as is necessary with traditional strain-gage installations. Ultrasonic instrumentation, along with standard pull-test equipment, enables nondestructive testing of various types of bolts installed in any medium.

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