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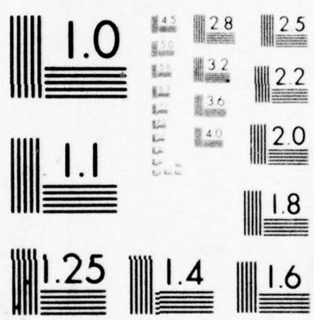

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TECHNICAL REPORT S-76-14

AN EVALUATION OF THE DESIGN AND APPLICATIONS OF YIELDABLE ROCK BOLTS

by

Wendell O. Miller

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This report serves as a compilation of developmental, design, and test data for three types of yieldable rock bolts which have been developed and tested. The three types of bolts (termed herein the South African, Bureau of Mines, and Omaha District rock bolts) represent the major thrusts in rock bolt developmental work to date. Much of the information presented was summarized from published reports and personal communications with the designers.

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20. ABSTRACT (Continued).

A rock bolt is a tension member which exerts force on a rock surface from a point of anchorage within the rock mass. The rock bolt's function is to hold the rock surface in situ. Continued excavation, dynamic loading, creep, or a combination of these three factors may result in considerable deformation of a rock mass after installation of the rock bolts. Therefore, a bolt that will yield without danger of breaking is needed in underground construction to protect the integrity of cavities and tunnels during their excavation and construction phases.

from front

The rock bolts evaluated in this study were of two basic types: the "die-thread" type (the South African and Bureau of Mines bolts) and the "plug-tubing" type (the Omaha District bolt). With both types of yielding mechanisms the physical shape or configuration of the component parts was shown to be of critical importance. For the two yieldable rock bolts the sensitivity of yield loads to construction methods appears to be comparable. The cost, however, is expected to be somewhat higher for the Omaha District mechanism.

All yielding mechanisms performed in accordance with design criteria under static and quasistatic loading conditions, but the Omaha District bolt has a quicker reaction time than either of the other two bolts. Under dynamic loading conditions both types of yielding mechanisms exhibited rate effects. Increases in displacement velocity of the bolts gave higher yield loads for the Bureau of Mines bolts, whereas measurements for the Omaha District bolts indicated the opposite trend, with slight decreases in yield load with increases in velocity. The types of resistance provided by each bolt tested were similar. Each was shown to provide about one-third of the resistance in the form of frictional resistance.

Both types of yieldable rock bolts are recommended for use in locations of incipient or suspected movements and displacements. A future limited laboratory testing program evaluating the creep and relaxation potential of the two types of yielding mechanisms is also recommended. The final recommendation for future testing is a full-scale field test in which the performance of the two basic types of yieldable rock bolts would be evaluated under dynamically loaded conditions.

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PREFACE

This report serves as a compilation of developmental, design, and test data for three types of yieldable rock bolts which have been developed and tested. While various organizations and institutions have worked with and considered the problem of a yieldable rock bolt, the three types presented in this report represent the major thrusts in developmental work to date.

All information reported on the South African yieldable rock bolt as well as details on the development and preliminary testing of the Bureau of Mines yieldable rock bolt were summarized from published reports and personal communications with the designers. The impetus for the report, however, was publishing information on the design and development of the Omaha District yieldable rock bolt, as well as the final test results on both the Omaha District and the Bureau of Mines yieldable rock bolts. This study addressed QCR 1.04.013.

This study was initiated by the U. S. Army Engineer Missouri River Division Laboratory (MRDL) and the U. S. Army Engineer District, Omaha (OD), in the 1960's. Transfer of the work units responsible for the study, i.e., the Rock Mechanics Section of the MRDL and the Protective Structures Branch of the OD in 1973, however, resulted in the functions being transferred to the U. S. Army Engineer Waterways Experiment Station (WES). The work performed by each work unit has been sponsored by the Office, Chief of Engineers (OCE), under O&MA funds. The work by WES was performed during the period of July 1974 to April 1976.

In preparation of this report, numerous reports and investigations were consulted and relied upon heavily. Of particular importance were various publications by, as well as personal communications with, W. D. Ortlepp, Rock Mechanics Engineer, East Rand Proprietary Mines Limited (ERPM), Boksburg, South Africa, concerning the development, design, testing, and effectiveness of yieldable rock bolts for shock or impulse loadings. Also of significant importance was an interim report, "Development of an Expandable Rock Bolt," prepared by L. A. Brown, MRDL, and a preliminary draft of testing results on "Extendable Rock Bolts," prepared by V. W. Sluka, OD. The final source of information consulted for this report was a Bureau of Mines Report of Investigations entitled "Laboratory Studies of Yielding Rock Bolts" prepared by J. P. Conway, S. M. Dar, J. H. Stears, and P. C. McWilliams. These reports were utilized extensively and served as the foundation upon which this report was developed.

This report was prepared by Mr. W. O. Miller under the general supervision of Messrs. J. S. Huie, Chief, Design Investigations Branch, and D. C. Banks, Chief, Engineering Geology and Rock Mechanics Division. Messrs. J. P. Sale and R. G. Ahlvin were Chief and Assistant Chief, respectively, of the Soils and Pavements Laboratory during the period in which this report was prepared.

Directors of WES during the preparation and publication of this report were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Mr. F. R. Brown was Technical Director. Mr. D. S. Reynolds was technical monitor for OCE.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
pounds (mass)	0.4535924	kilograms
pounds (force)	4.448222	newtons
kips (force)	4.448222	kilonewtons
foot-pounds	135.5818	newton-centimetres
foot-pounds per square foot	0.1460	newton-centimetres per square centimetre
kips (force) per square inch	6894.757	kilopascals
inches per second	25.4	millimetres per second
inches per minute	0.4233	millimetres per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
degrees (angular)	0.01745329	radians
square feet	0.09290304	square metres
pounds (force) per square inch	6894.757	pascals

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

AN EVALUATION OF THE DESIGN AND APPLICATIONS OF YIELDABLE ROCK BOLTS

PART I: INTRODUCTION

Definition of the Problem

1. A rock bolt is a tension member which exerts force on a rock surface from a point of anchorage within the rock mass. The rock bolt's function is to hold the rock surface in situ. Continued excavation, dynamic loading, creep, or a combination of these three factors may result in considerable deformation of a rock mass after installation of the rock bolts. Therefore, a bolt that will yield without danger of breaking is needed in underground construction to protect the integrity of cavities and tunnels during their excavation and construction phases.

2. The functional requirements of rock bolts include more than securing loose blocks or slabs of rocks. When used properly, rock bolts can maintain the spatial integrity of a rock mass, thus enabling the rock itself to support the major portion of loads resulting from stress relief caused by excavation. The ability of rock bolts to maintain loads while being subjected to deformations is thus of significant importance in rock excavation operations.

Background

3. While the need for rock bolts capable of maintaining load during large and rapid deformations was recognized much earlier, the first significant work on their development was not begun until the 1960's in South Africa. The deep, hard-rock, gold mines of South Africa utilized conventional rock bolts and passive supports, yet experienced frequent tunnel wall failures caused by stress changes. The failures generally resulted from large displacements which occurred as gradual displacements as well as violent rock bursts. As a result, a yieldable rock bolt was developed that used a "yielding" device near the point of anchorage as

reported by Ortlepp.[1] The device consisted of a smooth-bored die of internal diameter slightly larger than the rock bolt stud but appreciably smaller than the crest diameter of threads rolled on the stud.

4. In the United States, work on the development of yieldable rock bolts also began in the 1960's. The U. S. Department of Interior, Bureau of Mines, Spokane Mining Research Center (SMRC), developed and tested a bolt using the same basic yield mechanism as the South African bolt. At approximately the same time, the U. S. Army Corps of Engineers (USAE), Omaha District, were developing and testing their version of a yielding rock bolt. The Omaha District bolt used a hardened tapered steel plug drawn through a length of steel mechanical tubing as a yield device rather than the die-pulled-over-threads device.

Purpose

5. The purpose of this report is to present developmental, design, and test data on the yieldable rock bolt developed by the Omaha District. To facilitate an evaluation of the Omaha District yieldable rock bolt, data published on the performance of the two additional yieldable rock bolts, the South African type and the Bureau of Mines type, have been condensed and summarized in this report. The performances of the bolts are compared with each other based upon laboratory and/or field tests. The relative merits of each are discussed and particular emphasis is placed upon each bolt's response to static and/or dynamic loads.

Scope

6. This report presents a review of perhaps the three major thrusts in the development of yieldable rock bolts to date. The information presented on the South African yieldable rock bolt was condensed and summarized from publications of and communications with W. D. Ortlepp, as well as from test data furnished by him. The information on the Bureau of Mines yieldable rock bolt was obtained both from the Bureau of Mines and from a comprehensive testing program initiated by the

U. S. Army Engineer Waterways Experiment Station (WES). Invaluable information on the development and early testing was furnished by J. P. Conway. The testing program conducted by WES was performed at Lawrence Livermore Laboratory (LLL) of the University of California, Livermore, California, where the static and dynamic responses of the yielding mechanism were fully evaluated. Finally, this report presents the work performed by the U. S. Army Engineer Missouri River Division Laboratory (MRDL) and the Omaha District (OD), which was culminated by a comprehensive testing and evaluation program at WES. Actual testing of the Omaha District yieldable rock bolt was conducted at LLL concurrent with the testing of the Bureau of Mines yieldable rock bolt.

Terminology

7. Terminology used by Ortlepp, MRDL, OD, and Conway varied in describing the various yieldable rock bolts. For clarity, the term yieldable rock bolt will be used exclusively in this report to refer to each of the various types of rock bolts capable of maintaining a load during and after deformations, i.e. yieldable rock bolts, yielding rock bolts, extendable rock bolts, and expandable rock bolts. In addition, the yielding portion of the yieldable rock bolts will be referred to as the yielding mechanism, rather than yielding die or bolt-die system as used in several of the references.

8. Loads imposed upon the rock bolts will be described throughout this report as being either static, dynamic, or a combination of the two. Laboratory pull tests which are reported as static tests include creep, relaxation, and load loss tests, as well as quasistatic tests conducted at low velocities (up to approximately 0.017 in./sec*). Dynamic laboratory pull tests were conducted at both high and low velocities. Tests defined as low-velocity tests were conducted at a velocity of 1.39 in./sec, while the high-velocity tests utilized velocities ranging

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 5.

from 7.1 to 105.0 in./sec. Field static tests are defined as those field tests in which loads are imposed upon tensioned rock bolts by deformations resulting from continued excavation, creep, and in situ stresses, while field dynamic tests are defined as those tests in which the bolts were shock loaded by the use of decoupled explosive charges.

PART II: SOUTH AFRICAN YIELDABLE ROCK BOLT

Design and Development

9. The limited use of rock bolts to provide immediate support to tunnels or the temporary support of large chambers and shafts, which are subsequently lined with steel or concrete, fostered an experimental appraisal for evaluating the potential of rock bolting in South African gold mines. Although the confining stresses resulting from rock bolting are not large enough to produce any appreciable increase in the strength of solid rock, investigators (Ortlepp[1]) recognized early in the program that the stability of fractured rock is improved once reinforced by rock bolts.

10. The basic design requirements for rock bolts thus became evident, i.e. the support must act as soon as possible and maintain its restraining effect while yielding through appreciable displacements. Conventional rock bolts have the ability to supply the necessary early restraint when the proper size and spacing requirements are met because they can be tensioned during installation and have a modulus two or three times greater than that of the rock. The usefulness of conventional rock bolts is limited, however, because their yield capacity results from plastic deformation of the steel and is limited to a few inches (depending upon the length of the rock bolt).

11. To overcome the limitations of conventional rock bolts, a simple yielding mechanism was developed by Ortlepp[1] in the 1960's. This mechanism consists of a smooth-bored die of internal diameter slightly larger than the rock bolt stud but appreciably smaller than the crest diameter of the threads rolled on the stud (Figures 1 and 2). The stud passes freely through a conventional expanding anchor, then through the die, before terminating in several inches of rolled thread. The larger diameter of the thread secures the stud in the anchor until the imposed load exceeds a critical value. When this happens, the thread crests become deformed and are forced back into the thread grooves, permitting

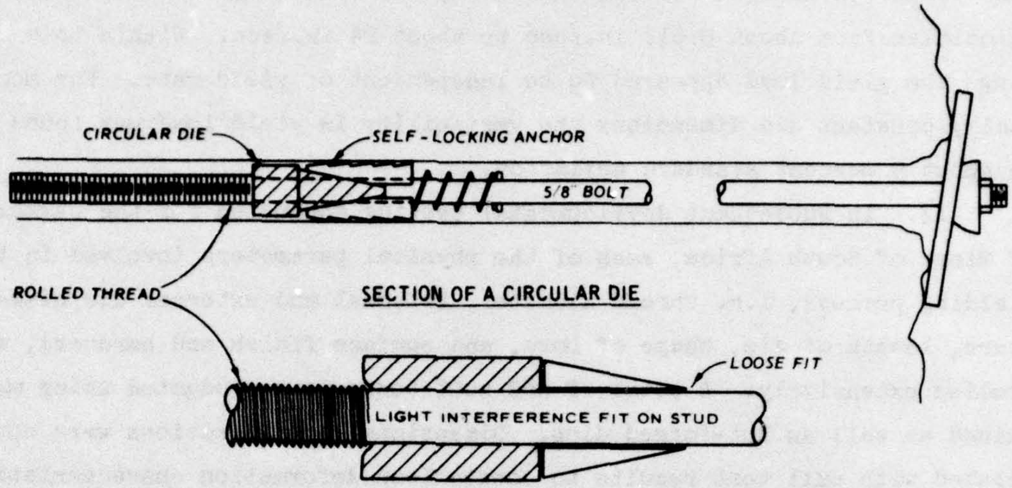


Figure 1. Schematic of South African yieldable rock bolt

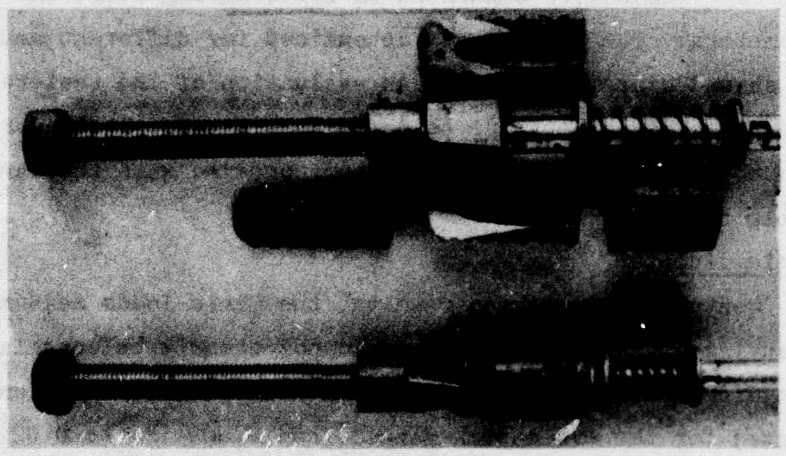


Figure 2. The ERPM constant-load yielding rock bolt

the bolt to move steadily through the die and anchor while maintaining a relatively constant resistance.

Laboratory Testing

12. Early investigations conducted on behalf of East Rand Proprietary Mines, Limited (ERPM), Johannesburg, South Africa, by The Corner House Laboratories[2] showed that the yieldable rock bolt concept was

functional. Available testing machines provided a range of displacement velocities from about 0.017 in./sec to about 24 in./sec. Within this range the yield load appeared to be independent of yield rate. For nominally constant die dimensions the variability in yield load was found to be about 9 percent standard deviation.

13. In subsequent developmental testing conducted for the Chamber of Mines of South Africa, each of the physical parameters involved in the yielding process, i.e. thread diameter, internal and external die diameters, length of die, shape of bore, and surface finish and hardness, was studied extensively. A total of 280 pull tests were conducted using machined as well as hot-forged dies. Dimensional considerations were correlated with pull test results to obtain load-deformation characteristics.

Thread diameter

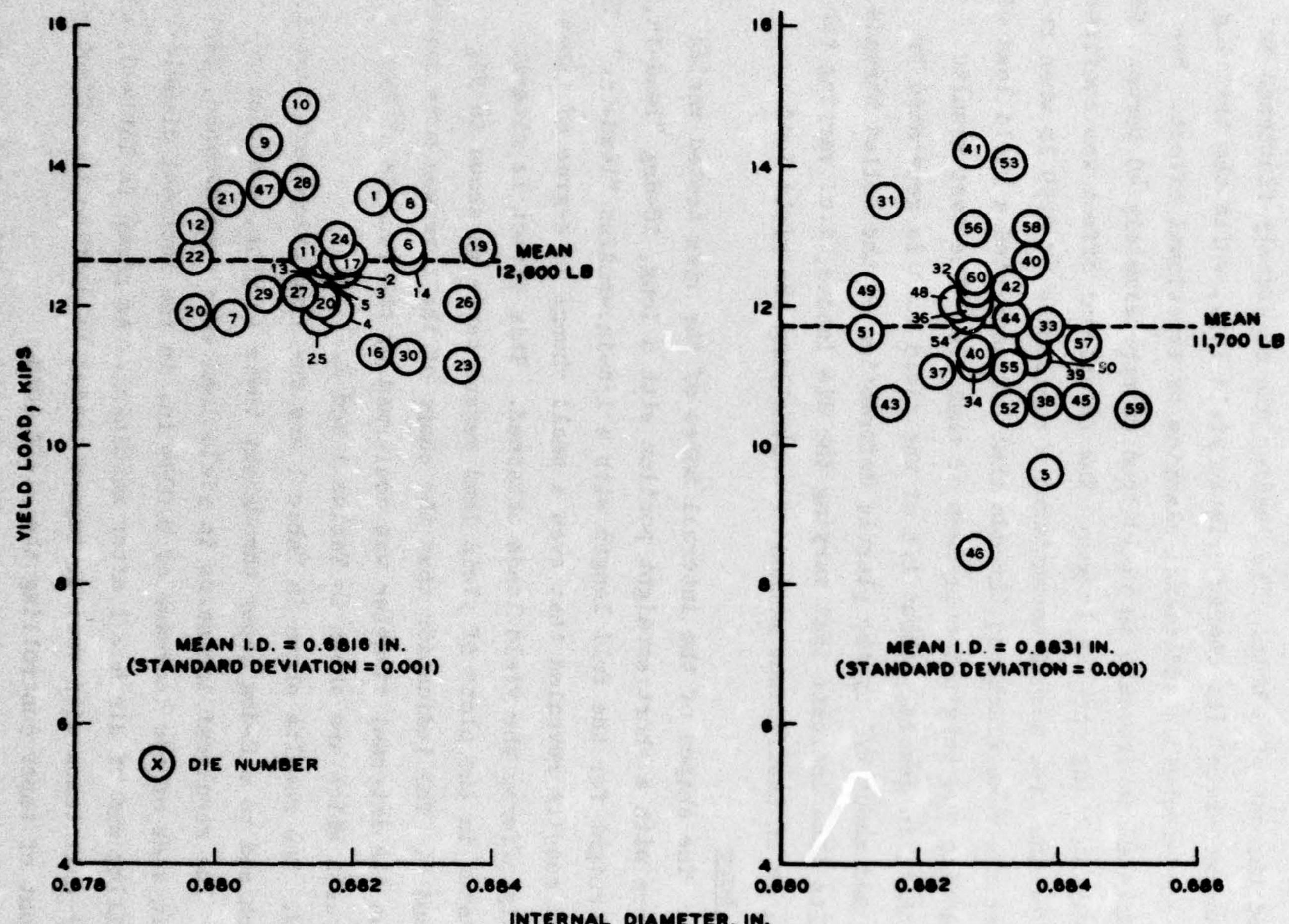
14. Pull tests were conducted on bolts having different mean thread diameters. The yield loads determined for different mean thread diameters showed close agreement. An evaluation of the test results indicated that the variations due to nonuniformity of the standard rolled threads on the bolts were negligible when compared with the variations attributable to the dies.

Internal die diameter

15. Contrary to expected results, the yield loads measured for dies of varying internal diameters could not clearly be correlated with the inside diameter. Although the differences in internal diameters of the dies used for the evaluation ranged from 0.002 in. to 0.02 in., the trend of decreasing yield loads with increasing internal diameters was not adequately demonstrated.

External die diameter

16. The amount a die is stretched elastically as it is forced over the raised threads of a bolt is a function of the wall thickness of the die. Therefore, the effect of the wall thicknesses of dies was investigated. The results of the pull tests indicated a slight bias of high loads obtainable with larger wall thicknesses, as shown in Figure 3. The differences, however, were minor when compared with other controlling parameters, as will be shown later.



a. 3/4" I.D. × 1-3/8" O.D.

b. 3/4" I.D. × 1-1/4" O.D.

Figure 3. Plots of yield load versus internal diameter for South African yielding mechanism

Length of die

17. To evaluate the effect of friction between the die and the rock bolt upon yield load, two dies were pulled together, in tandem, over the rolled threads of a bolt. The leading die completely flattened the threads and generated its characteristic yield load, while the trailing die only contributed an additional clamping or frictional effect. Results indicated an increase in yield load of approximately 40 percent for effectively doubling the die length. The frictional effect was confirmed when one of the dies tested encountered a resistance of 2250 lb when redrawn over the same flattened threads that had generated a yield load of 6250 lb during the original pull test of that die. The test results suggest that, in general, about 1/3 of the yield load is generated by friction and about 2/3 by the plastic deformation of the rolled threads. The results thus indicate that varying the die length, i.e. varying the friction, is an inefficient method of controlling the yield load.

Shape of bore

18. The shapes of the internal bores of the dies tested varied from a bore with a short straight portion with a long, 10-deg "lead-in," to one straight for the full length with a 1/8-in.-radius "lead-in." The pull test results revealed that even a small change in degree of taper materially affects the yield loads obtained. This effect is clearly demonstrated in the plots of yield load versus taper as shown in Figures 4 and 5. The indication that the shape of the bore was more important than its internal diameter was confirmed by the results of two direct tests which are shown in Tables 1 and 2.

19. The results shown in Table 1 are for dies which were tested, then machined to a 2-deg taper throughout their lengths, and then retested. The resultant increases in yield load were considerable, particularly in view of the increase of 0.0094 in. in the internal diameter of the trailing end of die No. 1 after machining. As shown in Table 2, additional pull tests with various tapers tended to confirm the effect of the amount of taper controlling the yield load.

20. Dies 3 through 5 (shown in Table 2), as well as die 2 previously tested, all had virtually the same internal diameter at the

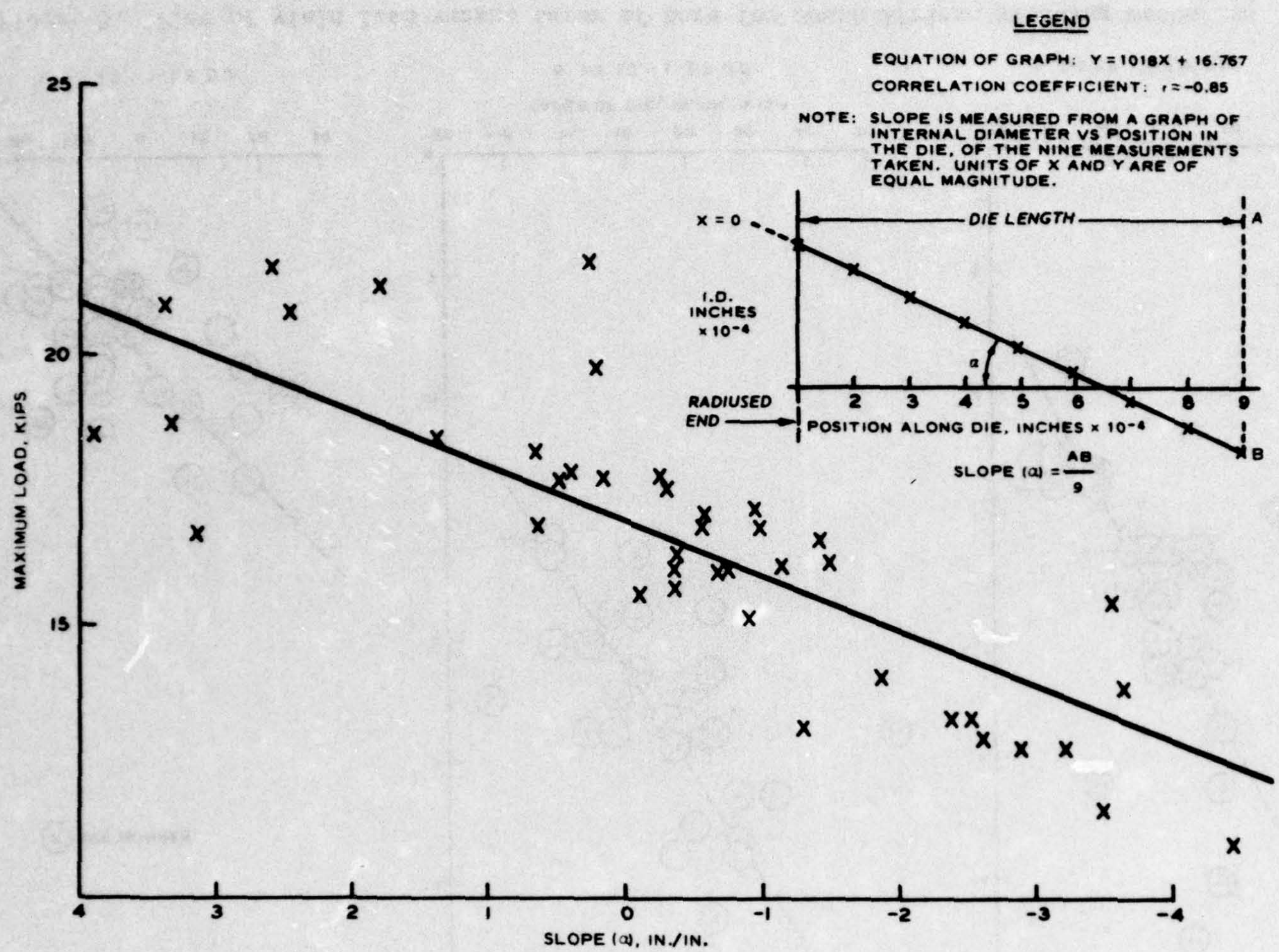


Figure 4. Plot of maximum load versus slope (taper) for South African yielding mechanism

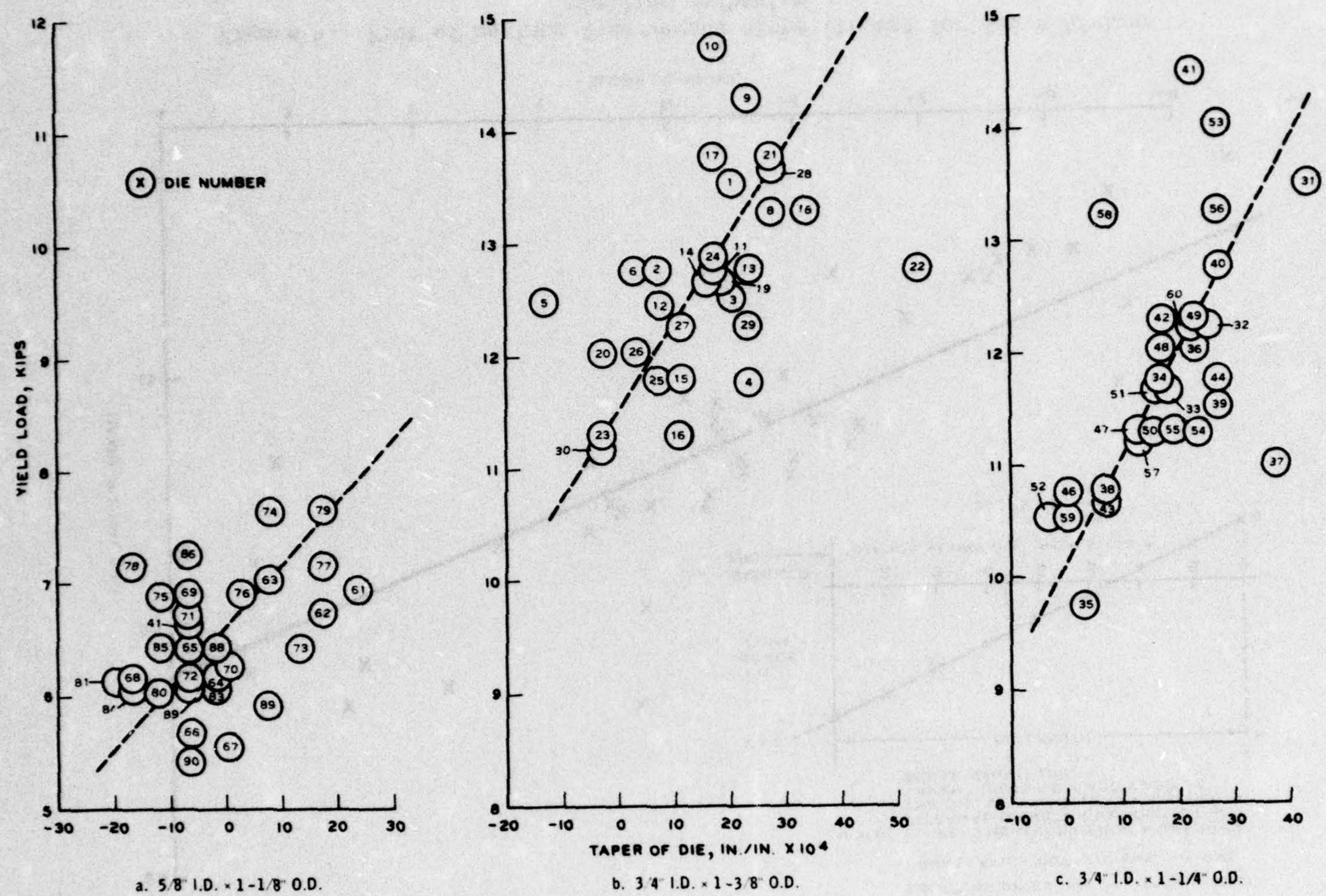


Figure 5. Plot of yield load versus taper of bore for South African yielding mechanism

Table 1

Results of Shape of Bore Tests

Die No.	Internal Diameter, in. Leading End	Trailing End	Mean Yield Load, lb
1 original	0.6858	0.6835	12,600
1 (2° taper)	0.7409	0.6929	19,700
2 original	0.6835	0.6811	12,200
2 (2° taper)	0.7311	0.6831	27,200

Table 2

Results of Additional Shape of Bore Tests

Die No.	Type of Taper	Internal Diameter, in. Leading End	Trailing End	Maximum Yield Load, lb
3	2°, fully tapered	0.7362	0.6839	29,450
4	2.6°, 2/3 tapered	0.7362	0.6831	28,450
5	5.2°, 1/2 tapered	0.7350	0.6831	21,400

trailing end. The yield loads measured for dies 2, 3, and 4 were not significantly different. The load of the 5.2-deg tapered die, No. 5, however, was sufficiently smaller to suggest that some shearing of the threads may have occurred as a result of the steepness of the taper.

Surface finish and hardness

21. Although no definite tests were performed, subjective assessments for the effects of surface finish were made during the testing operations. It did not appear that the surface finish had any significant effects on the yield loads.

22. The hardness of the tested dies varied between about 20 and 50 on the Rockwell C scale. Within this range there was no indication that variations in hardness had any effect on the yield load at the rates of strain which were used for the pull tests. The hardness of the dies (20 to 50 Rockwell C) relative to that of the bolts (10 to 12 Rockwell C) did, however, control the rate of wear of the dies tested.

Laboratory tests conclusions

23. The experimental observations indicated quite clearly that a

high and constant resistance to movement is generated by the die, mainly through the process of flattening the raised threads on the rock bolt. Appreciable additional resistance arises from the clamping or "frictional" effect of the elastically stretched die, which is dependent upon the die's external dimensions.

24. On the other hand, any tendency for the threads to be sheared, rather than flattened, results in much lower and more erratic yield loads, and probably induces less of a clamping or "frictional" effect from the die. Thus the shape of the bore must be designed to produce a progressive flattening of the threads. A profile of a parabolic nature was suggested as possibly the ideal shape. In practice, any profiles satisfying the equations presented in Figure 6 would probably be quite adequate in producing the desired yield loads. Indications are that the actual dimensional tolerances are not rigorous, provided that the shape requirements are satisfied.

Field Testing

25. To properly evaluate the yieldable rock bolt under field conditions, a location of incipient failure needs to be rock bolted and instrumented for long-term observation. However, due to the improbability of predicting the location of a naturally occurring failure, it was decided by Ortlepp[1] to artificially induce failure, under controlled conditions, in a specially prepared shaft.

26. The only means of causing failure, with some degree of control, appeared to be controlled peripheral blasting. Although not geometrically realistic, blasting would at least provide the large displacements which accompany gradual, progressive tunnel failure and, at the same time, provide the high-velocity displacements which are believed to be characteristic of rock bursts.

Test site

27. A drift in one of ERPM's gold mines in South Africa was chosen as a test site. At a depth of 9400 ft, the development of a main fan installation was in progress in a somewhat argillaceous quartzite which

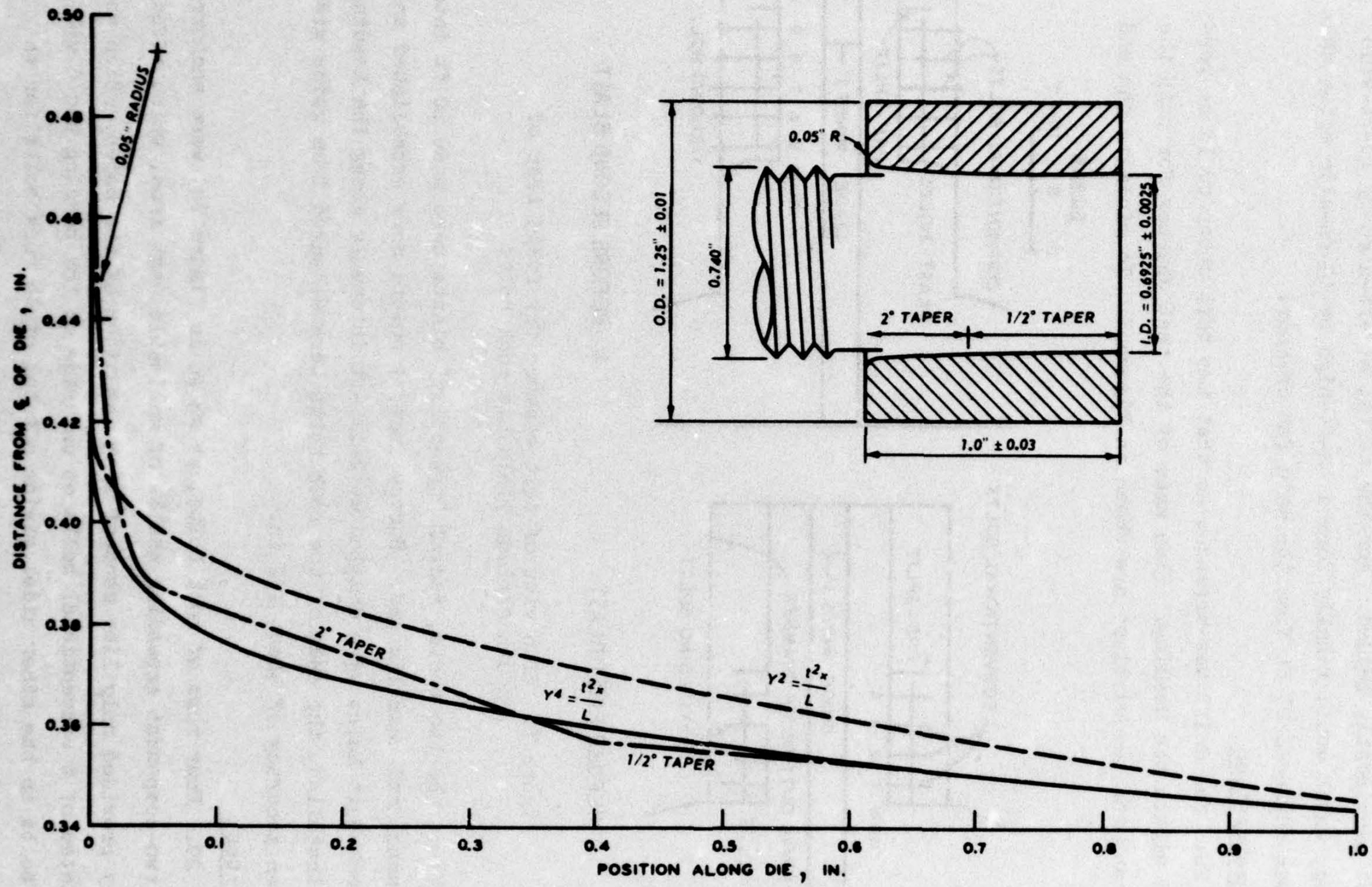


Figure 6. Recommended bore profiles for 3/4-in. South African yielding dies

was not prominently bedded. For the tests, a 9-ft-high by 10-ft-wide heading, which would finally form a 12-ft-high by 19-ft-wide motor chamber, was advanced 25 ft from the main fan chamber.

Site preparation

28. The drift was arranged so that two test shots could be performed within the heading. Plan maps of the test chamber for both the first and the second blast are shown in Figure 7. To minimize the end

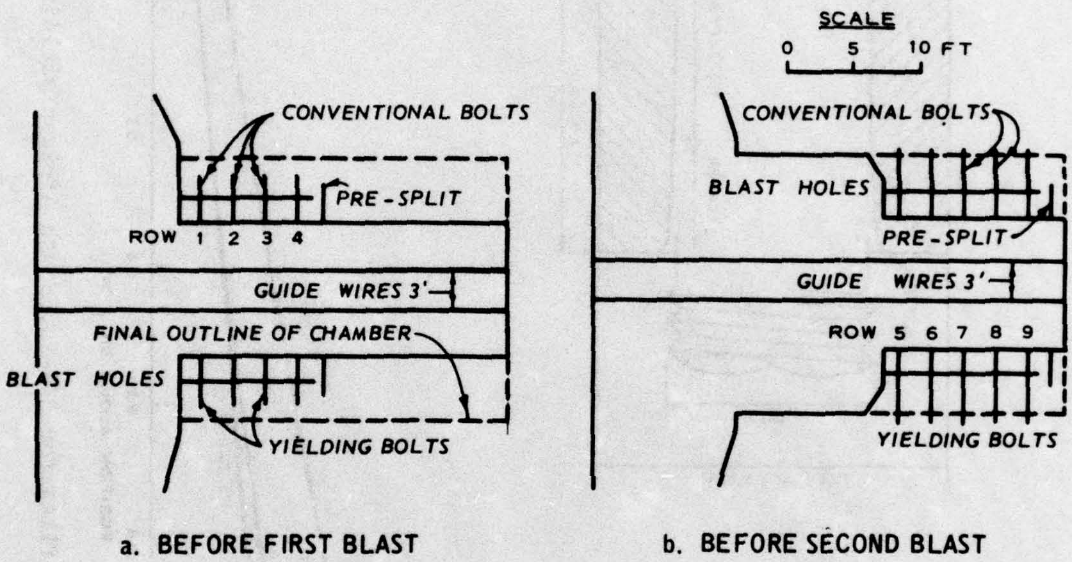


Figure 7. Plan view of test chamber for field test of South African yieldable rock bolts

effects of the two tests, radial "pre-split" blasts were made 10 ft into the tunnel and near its end. Survey control points were established and the rock-bolt holes were drilled at 2-1/2-ft intervals along the heading. When installed, the ends of the rock bolts were measured from guide wires with an accuracy of about 1/2 in.

First test

29. Four rows of rock bolts, as shown in Figure 7a, were anchored with two-component expanding shells of malleable cast iron, which effectively provided only line contact with the sides of the holes. Each row consisted of 6 conventional bolts on one side of the heading and 6 yieldable bolts on the other side, giving a total of 48 rock bolts for the

test. All of the rock bolts were 5/8-in.-diam, high-tensile-strength studs, with spring-loaded, self-locking anchors. The bolts were tensioned against a double layer of 8-gage, linked wire mesh (2-in. mesh size) which covered the interior surface of the tunnel. The rock bolts were effectively 4 ft long, with an additional 9 in. of yielding thread on the yielding bolts.

30. Acceleration of the tunnel walls was attained by placing explosives in 24 peripheral holes, 10 ft long, and uniformly spaced about 17 in. apart, which were drilled parallel to the axis of the tunnel, about 2 ft from its surface. The explosive charges consisted of 4-in. by 7/8-in. cartridges of 40 percent dynamite, uniformly spaced to fill 15 percent of the volume of each hole. The decoupled charges were detonated simultaneously to provide the desired impulse loading to the tunnel wall. The energy of the blast was sufficient to split and eject the rock, and destroy all the bolts and mesh, leaving a clean "post-split" surface as shown by the typical profile in Figure 8a.

31. Only 11 of the 48 rock bolts remained anchored or partially anchored in the tunnel walls after the blast. Four of the 11 were conventional bolts which were partly but not completely dislodged and, in two of these, the domed plates had failed. The remaining 7 were yieldable rock bolts in which all 9 in. of the yielding threads had been forced through the dies, leaving the anchors and dies still locked in their respective holes. A close examination of the 37 bolts which had failed completely revealed that the failures were caused by ineffective anchorage. The metal along the contact line between the anchor and rock was so highly stressed that it sheared and was rapidly abraded away.

Second test

32. For the second test, 5 rows of rock bolts were used, as shown in Figure 7b. Three of the rows used the two-component anchors, as in the first test, while the remaining two rows used an improved type of anchor with three expanding segments. Again, each row consisted of 6 conventional bolts on one side of the heading and 6 yieldable bolts on the other side.

33. The arrangement of the blasting holes used in the second test

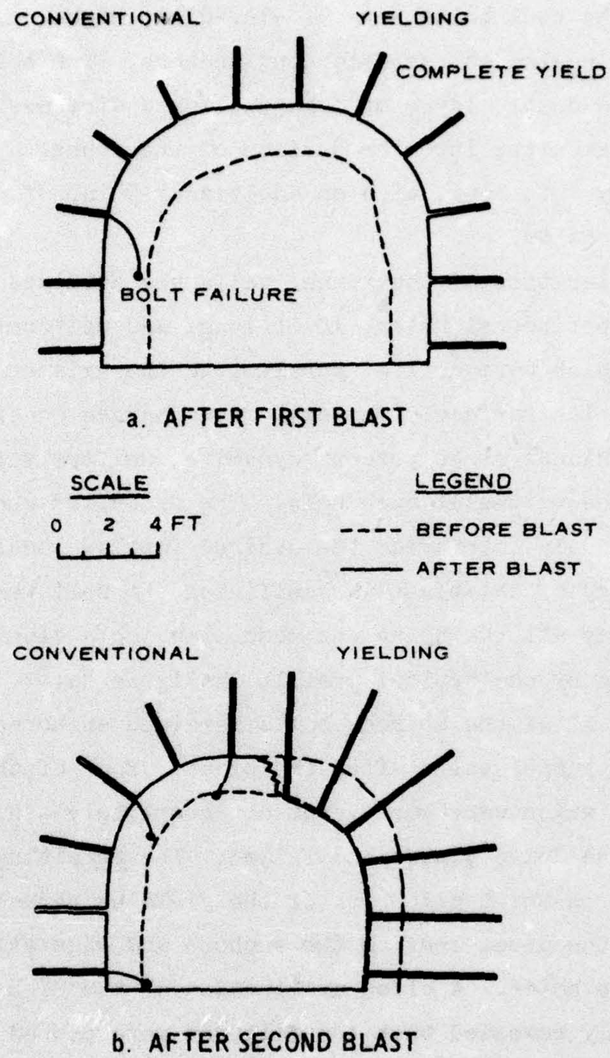


Figure 8. Typical profiles after blasting in field tests of South African yieldable rock bolts

was the same as that used in the first test. The spacing of the 40 percent dynamite cartridges, however, was increased in the blast holes to the extent that they filled only 8 percent of the volume of each hole, rather than 15 percent. The charges were detonated simultaneously, and the blast completely split and fragmented the conventionally rock-bolted wall, while the wall bolted with the yieldable bolts remained in place, as shown by the typical profile in Figure 8b.

34. In the conventionally bolted rock wall, of the 18 bolts equipped with two-component anchors, 2 failed in tension, 8 were completely dislodged, and the remaining 8 had the rock broken away from them. Tensile failure occurred in 6 of the 12 bolts equipped with the three-segment anchors, 2 completely dislodged, and the rock had broken away in 4 instances.

35. In the rock wall bolted with yieldable rock bolts, a visible split developed between the peripheral blasting holes but no bolts failed, and the mesh remained completely intact. No rock was dislodged except at the crown of the tunnel adjacent to the conventionally bolted side. Some fracturing of the rock surface was visible behind the wire mesh, and measureable displacement relative to the guide wires was observed at the ends of 12 of the total of 30 yielding rock bolts.

Applicability of test procedure

36. Very little is known about the mechanism of rock bursts in tunnels; however, it has been conceived that damage could occur in two distinctly different ways. The passage of a shock wave arising from some large energy release, originating at some distance from the tunnel, could accelerate and eject already fractured and partially detached slabs of rock, or under certain external loading conditions, a sudden enlargement of the fracture envelope around the tunnel itself could constitute an energy source resulting in damage. This latter type of damage probably occurs less frequently than the first, but in its effects is more analogous to the artificially induced failure of this type of experiment.

37. For a cylindrical excavation at a 9000-ft depth, it was reported by Cook[3] that an increase in radius of the fracture envelope from 6 to 8 ft would be accompanied by an energy release of the order of about 5×10^3 ft-lb per sq ft of tunnel surface. The energy imparted to the rock walls by the test blasts was estimated only within very wide limits. Estimates by Ortlepp[1] for the second test indicate that there was approximately 0.06 lb of explosive per sq ft of tunnel. The energy involved was thus less than 3×10^4 ft-lb per sq ft if it is assumed that the

total chemical energy equivalent of 1 lb of explosive is about 5×10^5 ft-lb, and that a considerable portion of the chemical energy was dissipated as heat and noise. Since it is unlikely that the efficiency of the blast was less than 30 percent, the energy involved in damaging the tunnel walls during the second blast was probably 10^4 ft-lb per sq ft, which is within an order of magnitude of that estimated for rock bursts.

Field test conclusions

38. An analysis of the stability of fractured walls in a tunnel at depth indicates that the most important requirement of support is the ability to yield while maintaining constant resistance. Although no refined measurements were made, the visual evidence of these tests conclusively showed that yieldable rock bolt support was much more effective than conventional bolting in preventing damage caused by impulse loading. In this respect, the analysis appears to be substantiated by the experimental results. Based upon the energy considerations of the artificially induced failure of the second test, it seems probable that a tunnel supported by yieldable rock bolts and mesh could survive all but the most severe rock bursts.

39. A cursory evaluation of progressive failure, involving large displacements over a relatively long period of time, indicates again that the yieldable rock bolt is superior to conventional rock bolts. In a slow-displacement situation, the ductility of 5-ft-long bolts would permit movement on the order of 4 or 5 in. before the yield limit would be reached and a failure occur. On the other hand, yieldable rock bolts could be provided with an additional capacity for movement three or four times greater. This would greatly increase the probability that the external load would diminish more rapidly than the "fracture strength" and stable equilibrium would be attained.

PART III: BUREAU OF MINES YIELDABLE ROCK BOLT

Design and Development

40. The U. S. Department of Interior, Bureau of Mines, Spokane Mining Research Center (SMRC), began a program of investigation on the development and use of yieldable rock bolts in the early 1970's. Information published by Ortlepp and Reed[4] (as summarized in Part II of this report) about the South African yieldable rock bolt served as a stimulus for beginning the Bureau of Mines developmental program. After correspondence with Ortlepp and Reed, Mr. John P. Conway of the SMRC developed the Bureau of Mines yieldable rock bolt, shown in Figure 9, as a

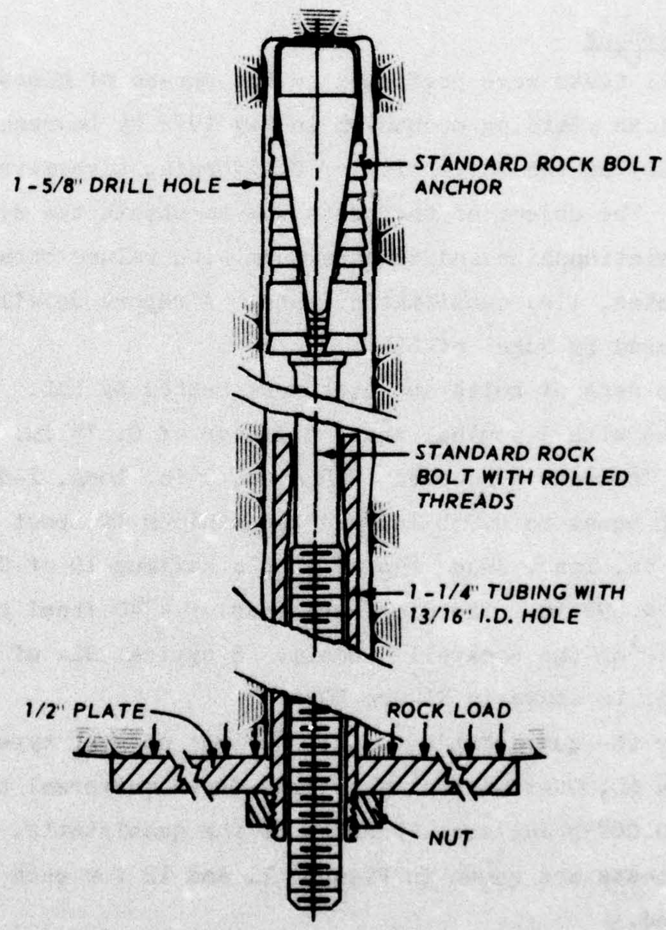


Figure 9. Bureau of Mines yieldable rock bolt

modification of the South African design.

41. Initial trials with a bolt made similar to the South African bolt presented anchorage problems with the yielding mechanism located near the point of anchorage. For this reason it was decided to move the yielding mechanism from the point of anchorage to the outside end of the rock bolt. Subsequent to the development of the Bureau of Mines yieldable rock bolt, samples of the South African bolt were obtained and comparisons were made. The failure mechanisms of the two are basically the same and the same ultimate goals are attained with each.

Laboratory Testing

Preliminary testing

42. Pull tests were performed on the Bureau of Mines version of the South African yielding mechanism in May 1972 by Lawrence Livermore Laboratory (LLL) of the University of California, Livermore, California, for the SMRC. The object of the tests was to obtain the dynamic load-deformation relationships and compare them with values obtained at low deformation rates, i.e. quasistatic tests. A report detailing the findings was prepared by Hoge[5] of LLL.

43. Two sets of bolts and dies were tested by LLL. Each set consisted of bolts with a nominal shank diameter of 0.675 in. and 3/4-10 UNC threads. The sets consisted of 5 dies, 2 in. long, 1-deg taper, with the maximum ID equal to 0.738 in. and the minimum ID about 0.690 in., and 5 dies, 1 in. long, 3-deg taper, with a maximum ID of 0.738 in. and minimum ID of 0.690 in. The dies were made of 4340 steel hardened to between 32 and 40 on the Rockwell C scale. A typical die of the second set, as tested, is shown in Figure 10.

44. For the quasistatic tests, one test on each type of die was conducted on a 60,000-lb-capacity, Tinius-Olsen universal test machine at a rate of 0.00833 in./sec. Results of the quasistatic, as well as the dynamic, tests are shown in Figures 11 and 12 for each set of bolts and dies tested.

45. In performing the dynamic pull tests, two different kinds of

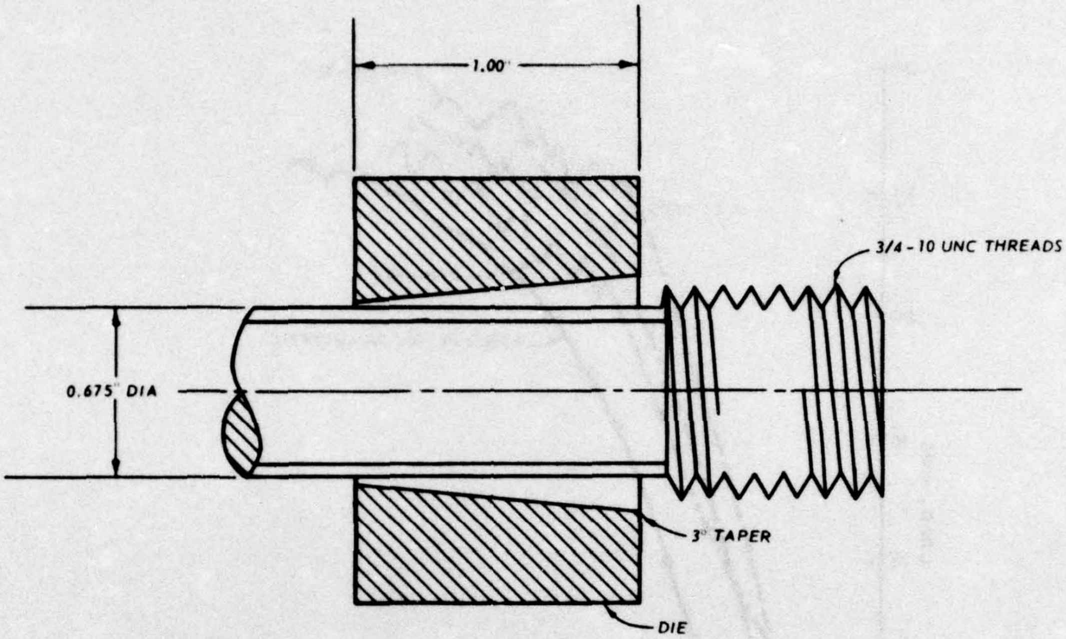


Figure 10. Schematic sketch of Bureau of Mines rock bolt yielding mechanism

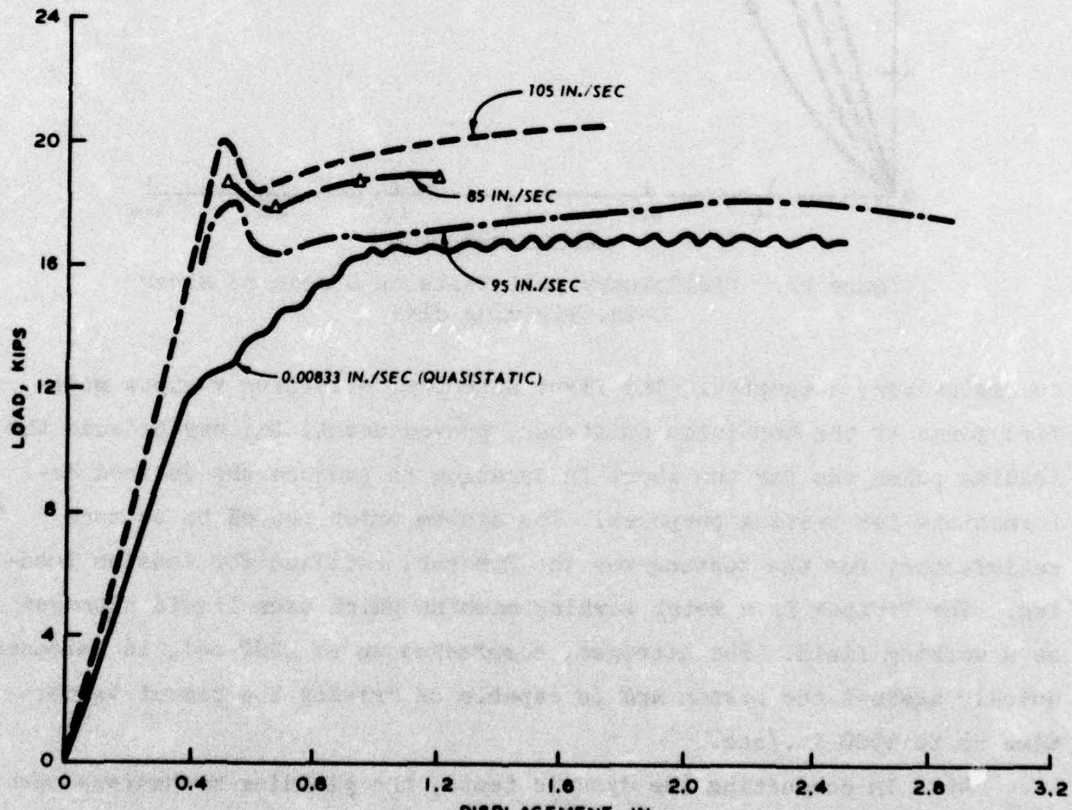


Figure 11. Preliminary pull tests on Bureau of Mines 1-in. yielding dies

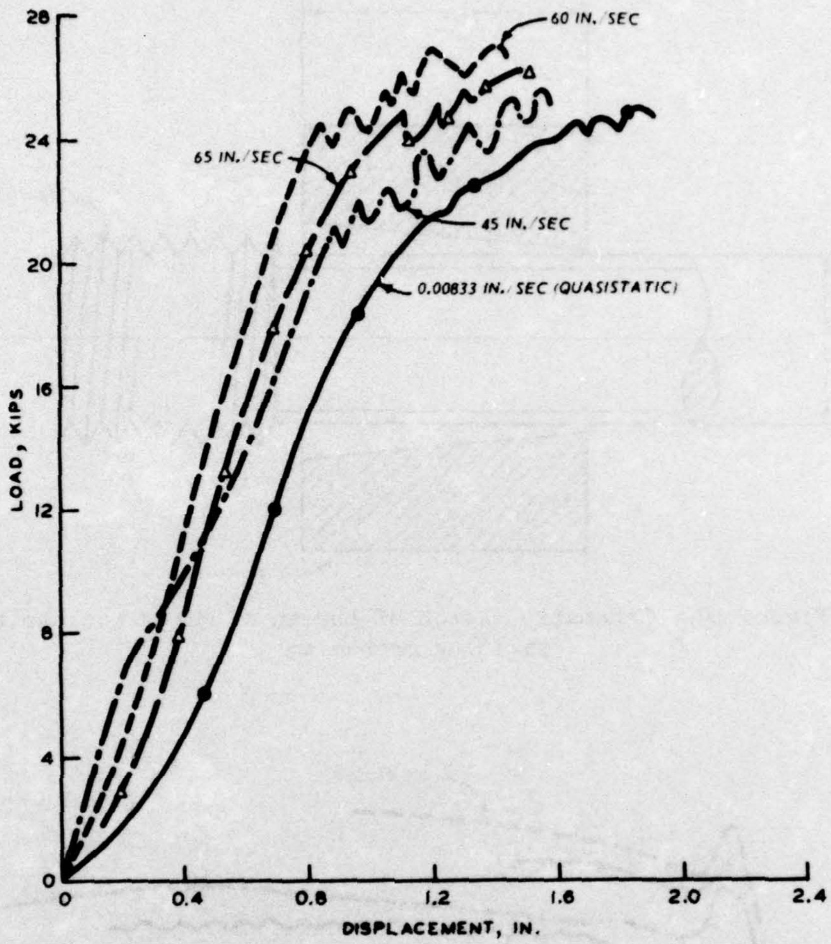


Figure 12. Preliminary pull tests on Bureau of Mines 2-in. yielding dies

apparatus were attempted. The first attempts, utilizing various modified forms of the Hopkinson split-bar, proved unsatisfactory because the loading pulse was far too short in duration to produce the desired deformations for testing purposes. The system which proved to be more satisfactory for the testing was the Dynapak, modified for tension loading. The Dynapak is a metal working machine which uses liquid nitrogen as a working fluid. The nitrogen, compressed up to 2000 psi, is released quickly against the piston and is capable of driving the ram at velocities up to 1500 in./sec.

46. In conducting the dynamic tests, the yielding mechanisms were

held in a holding fixture, as shown in Figures 13 and 14. As designed, the system required that the rock bolt shank be threaded with 5/8-11 UNC threads. The threaded shank was attached to the stationary part of the Dynapak and the end plug to the moving part. A tension load was thus applied between the die and the shank. For testing purposes, the ram of the Dynapak was placed very close to the tension fixture loading plate so that the loading would be less of an impact type. Deformation velocities of 45 to 105 in./sec were obtained.

47. These tests were successful for loading the 1-in. dies; however, they were only partially successful for the 2-in. dies, as the threaded part of the shank failed after about 1 in. of travel. The results of these tests, as previously stated, are shown in Figures 11 and 12.

Preliminary test results

48. These tests reconfirmed the South African test results that the yieldable rock bolt system appears to be a suitable means of absorbing the energy from a dynamic pulse load. The results obtained tended to indicate that dynamic loading produces slightly higher loads than quasistatic loading. Loads during the first part of deformation, however, appeared to be more affected by loading rates than those occurring at larger deformations.

49. Visual examination of the dynamically tested bolts showed a rougher type of deformed thread surface, suggesting the possibilities of localized melting or even spot welding. A darker color was also observed on the dynamically tested threads, confirming the occurrence of very high temperatures. The Rockwell superficial hardness values, 30-N, which were determined on both the dynamically and quasistatically deformed threads were of particular interest. The hardnesses for the various materials are as follows:

a. Shank material: 30 to 35

b. Dynamically deformed threads: 42 to 49

c. Quasistatically deformed threads: 45 to 50

Thus, the threads hardened when deformed, contrary to the expected softening by hot working. Also of particular interest were the only slight

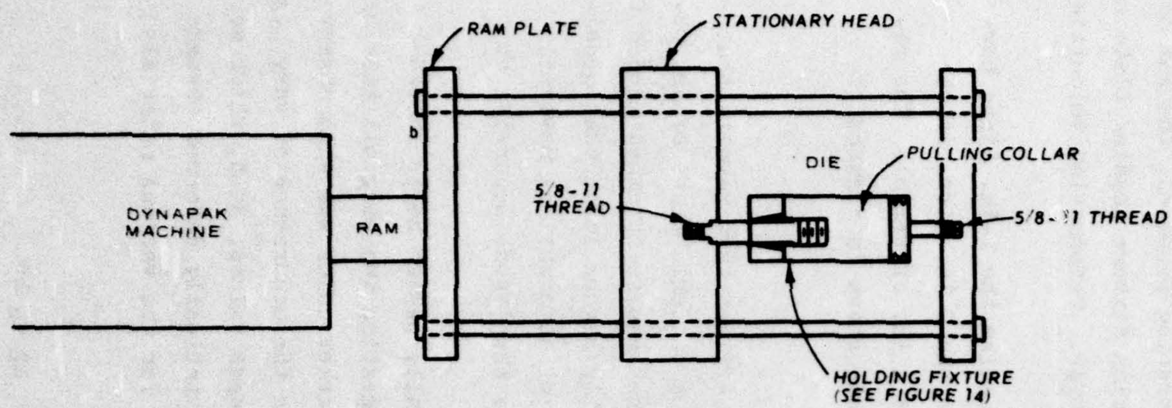


Figure 13. LLL dynamic testing setup

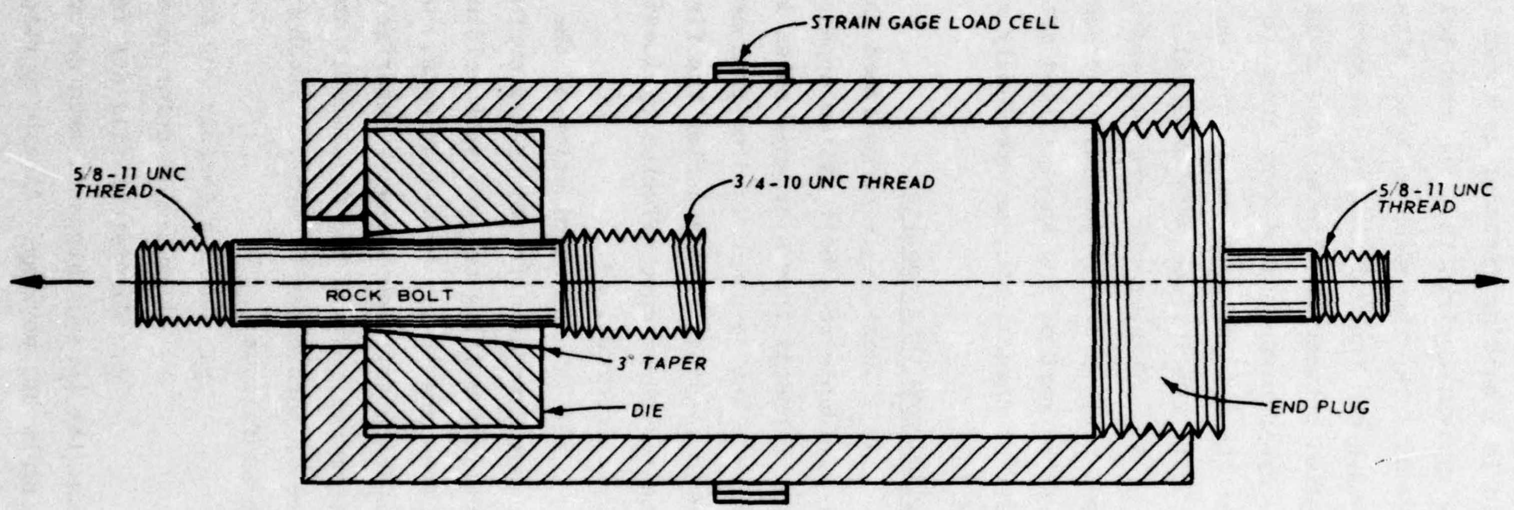


Figure 14. LLL yielding mechanism holding fixture

differences noted between the threads tested statically and dynamically.

Final tests

50. In an effort to more fully understand and evaluate the yielding mechanism utilized for the South African and the Bureau of Mines yieldable rock bolts, additional pull tests were performed by LLL for the WES. To accomplish this evaluation, a testing program was set up with three phases: (a) a quasistatic load test run at a velocity of 0.017 in./sec; (b) low-velocity dynamic tests run at a velocity of 1.390 in./sec; and (c) high-velocity dynamic tests run at velocities varying from 7.087 to 41.929 in./sec. A total of 6 yielding mechanisms were tested with 1 quasistatic test, 2 low-velocity tests, and 3 high-velocity tests being performed. The dynamic tests were run to displacements of 1.555 to 3.300 in., while the quasistatic test was run to a displacement of 6.693 in. Data were recorded in terms of force and displacement.

51. The quasistatic test was performed on a 112.4-kip (500-kN), closed-loop, servo-controlled test machine, and standard load and deformation measurements were made. The yielding mechanism was tested at a constant rate of 0.017 in./sec, and the results in terms of load versus displacement are shown in Figure 15.

52. The two low-velocity tests were also performed on the closed-loop, servo-controlled test machine. The displacement velocity (1.390 in./sec) was outside the rating of the test machine; however, auxiliary measurements confirmed that the displacement-time curve did not deviate from linearity by more than 5 percent, thus indicating that a reasonably constant velocity was maintained. Results of both the low-velocity tests in terms of load versus displacement are shown in Figure 16.

53. The high-velocity tests were performed at LLL's hydraulic shaker facility. The bolts were loaded by a hydraulic actuator under the control of a Mod Comp III computer. The computer also served as a data acquisition and data reduction device. Instrumentation was more extensive for the high-velocity tests than for the two preceding types of tests. The instrumentation utilized was as follows:

<u>a</u>. An in-line load cell was used to sense load.

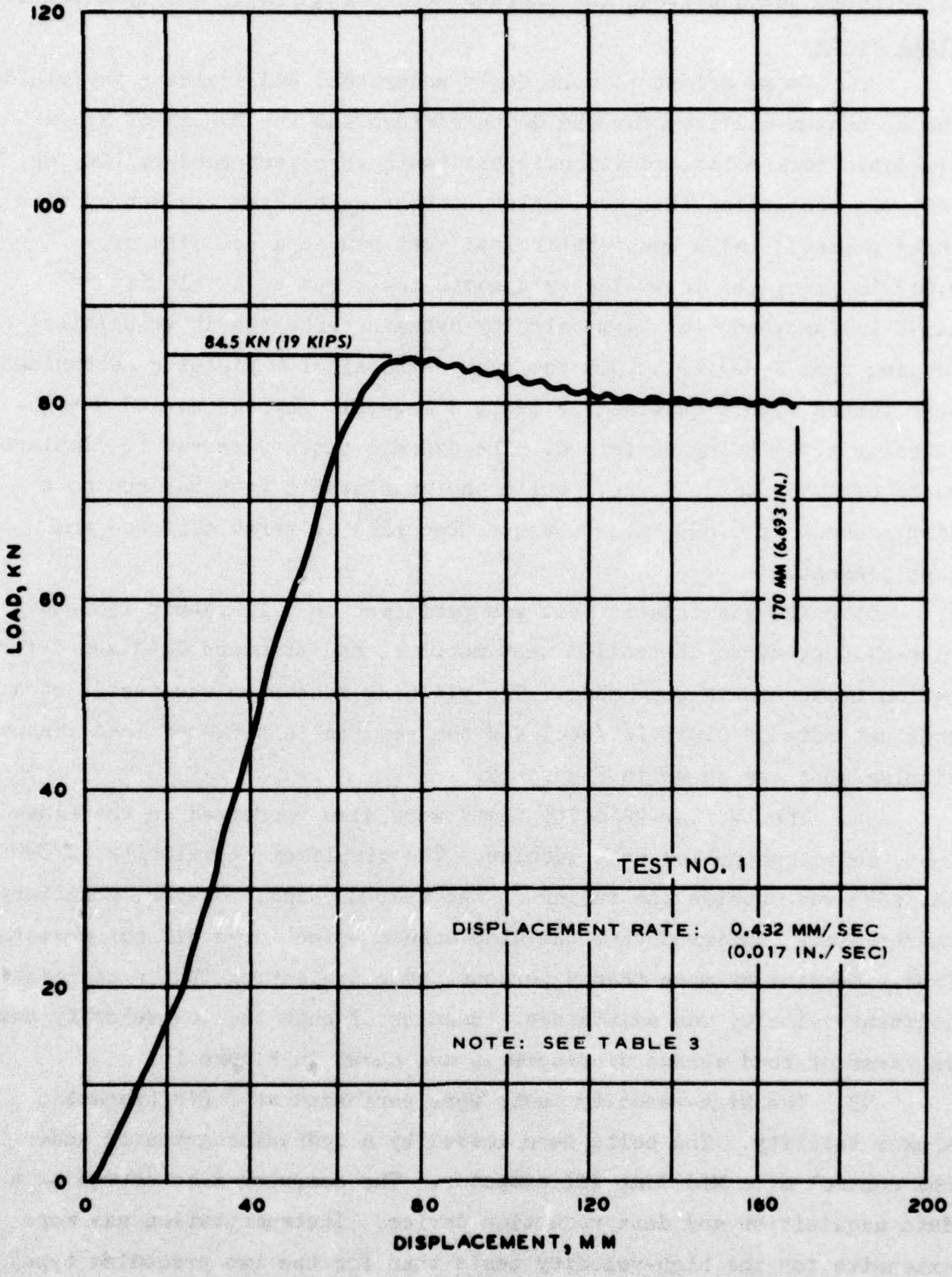


Figure 15. Quasistatic pull test; Bureau of Mines yielding mechanism

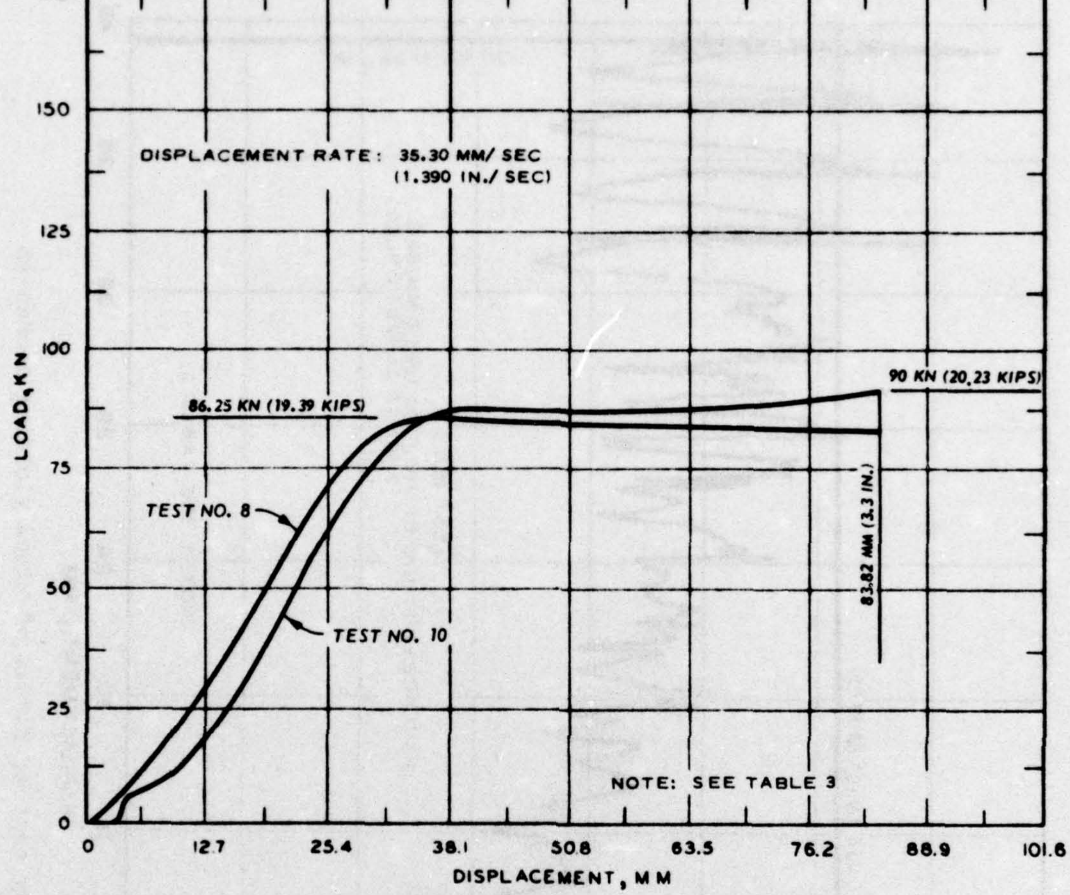


Figure 16. Low-velocity pull tests; Bureau of Mines yielding mechanism

b. An accelerometer mounted on the actuator load foot was used to sense acceleration.

c. A transducer built into the actuator mechanism was used to sense displacement of the loading ram.

d. A dynamic rated slide potentiometer measuring directly between the rock bolt shank and its deforming body was used to sense rock bolt displacement.

54. Results of the 3 high-velocity tests as reported by Tatro (Appendix A of this report) in terms of load versus displacement are shown in Figures 17 through 19. Constant rates of displacement were not achieved during the tests and, therefore, measurements of displacement rates versus time were recorded. These measurements, as well as

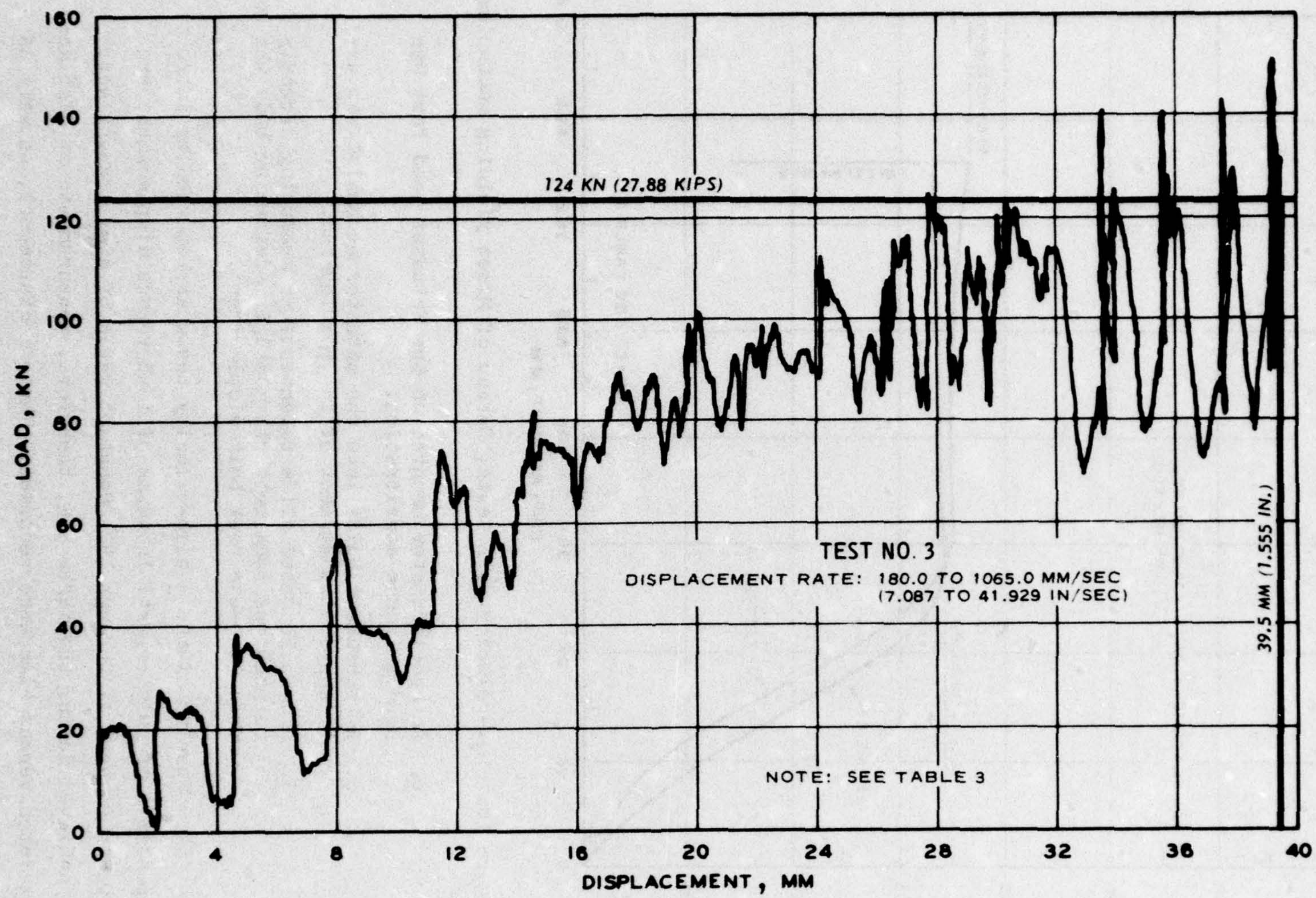


Figure 17. High-velocity test 3; Bureau of Mines yielding mechanism

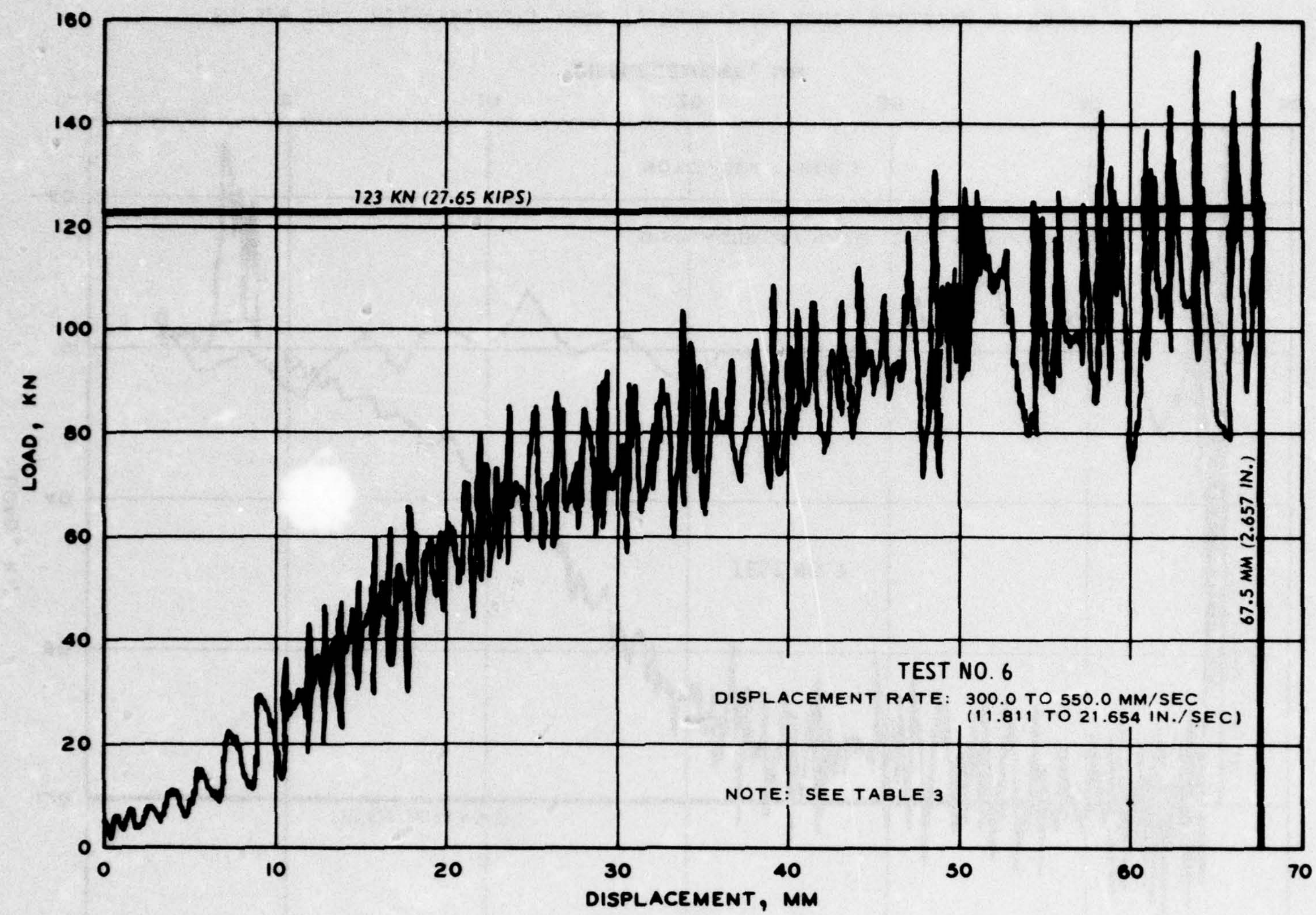


Figure 18. High-velocity test 6; Bureau of Mines yielding mechanism

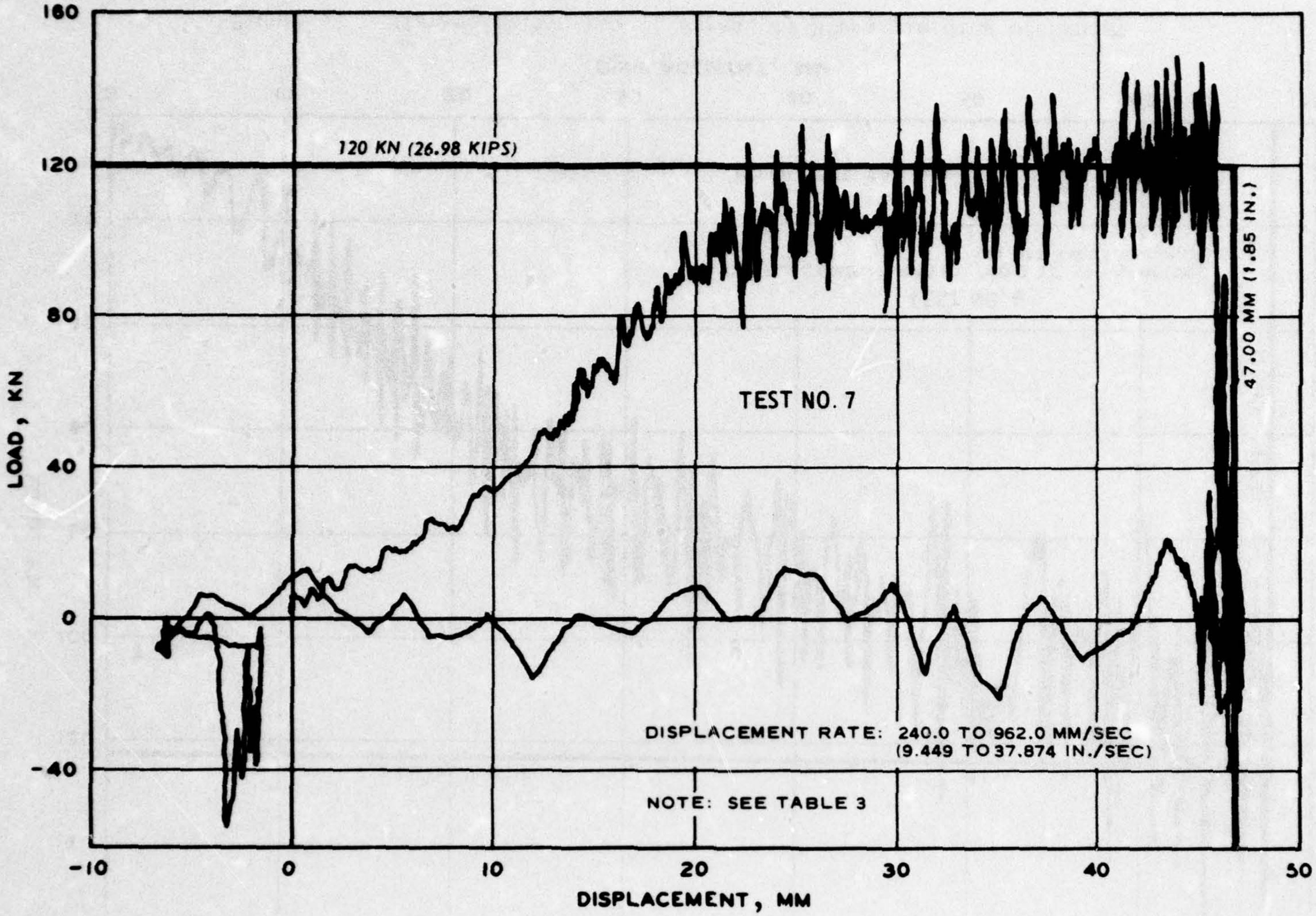


Figure 19. High-velocity test 7; Bureau of Mines yielding mechanism

load versus time and displacement versus time, are presented in Appendix A (LLL's final report on the laboratory test results).

Final test results

55. The results of the final pull tests performed on the Bureau of Mines rock bolt are summarized in Table 3. The results indicate an increase in load capacity with increases in displacement rates. Due to the closeness of the quasistatic and low-velocity test results it is probable however, that the effect of displacement rate on load capacity is not realized unless the velocities exceed 1.390 in./sec (the low-velocity displacement rate).

Table 3

Bureau of Mines Yielding Mechanism Pull Test Results

Test No.	Load	Joint Displacement	Joint Velocity		Remarks
1	19,000 lb 84,500 N	6.693 in. 170.00 mm	0.017 in./sec 0.432 mm/sec		Quasistatic test
8	19,390 lb 86,250 N	3.30 in. 83.82 mm	1.390 in./sec 35.300 mm/sec		Low-velocity test
10	20,230 lb 90,000 N	3.30 in. 83.82 mm	1.390 in./sec 35.300 mm/sec		Low-velocity test
3	27,880 lb 124,000 N	1.555 in. 39.50 mm	41.929 in./sec 1,065.0 mm/sec	7.087 in./sec 180.0 mm/sec	Shank yielded under dynamic load in all cases
6	27,650 lb 123,000 N	2.657 in. 67.50 mm	21.654 in./sec 550.0 mm/sec	11.811 in./sec 300.0 mm/sec	Velocity dropped during latter part of loading
7	26,980 lb 120,000 N	1.85 in. 47.00 mm	37.874 in./sec 962.0 mm/sec	9.449 in./sec 240.0 mm/sec	Last dynamic test. Fixturing failed

56. The rock bolts tested yielded in the shank position by about 1.969 in. (50 mm) during the high-velocity tests. The yieldings, plus the unsteady deformation characteristic of the threaded portion, contributed to the widely varying velocity-time response. The unsteady deformation of the bolts was probably enhanced by the fact that the long extender rod which coupled the bolt to the anchor contributed a significant amount of yield to the test spring. The results could possibly have

been improved by replacing the extender rods with a more rigid structure.

57. The results shown in Figure 19 represent the last dynamic test performed since the loading fixture at the end opposite the actuator failed. The failure is indicated in the figure by the decrease in load followed by displacement in the negative direction.

Field Testing

58. In the early part of 1974, a field test was begun using the Bureau of Mines yieldable rock bolts. The test consisted of the field installation of 134 yieldable rock bolts at one of the Coeur d'Alene mines. The material is a very hard quartzite, and to the present, there have been no creep or movement problems at the site. The bolts were surveyed using a closure station, and readings are being made on the bolt tips periodically. To the present time, no significant movements have been noted and the surveillance is being continued.

PART IV: OMAHA DISTRICT YIELDABLE ROCK BOLT

Design and Development

59. In the early 1960's, possibly prior to or at least concurrent with the work by Ortlepp on the South African yieldable rock bolt, the Omaha District began work on the development of a yieldable rock bolt. Work on numerous Corps of Engineers projects involving the design and testing of dynamically loaded sites served as an impetus for the development of the concept and the eventual design of a prototype yieldable rock bolt.

60. It was recognized that the strengthening of rock around an underground opening against shock effects requires rock bolts that are capable of absorbing the large deformations which result from bulking of the rock as it is crushed. Laboratory tests conducted for the Omaha District by the MRDL provided preliminary data for designing a yieldable rock bolt which yields at approximately 80 percent of the rock bolt steel yield load.

61. The yield load for the bolt is controlled by the strain energy required to draw a hardened tapered steel plug through a length of steel mechanical tubing (Figure 20). The axial force developed by the yielding

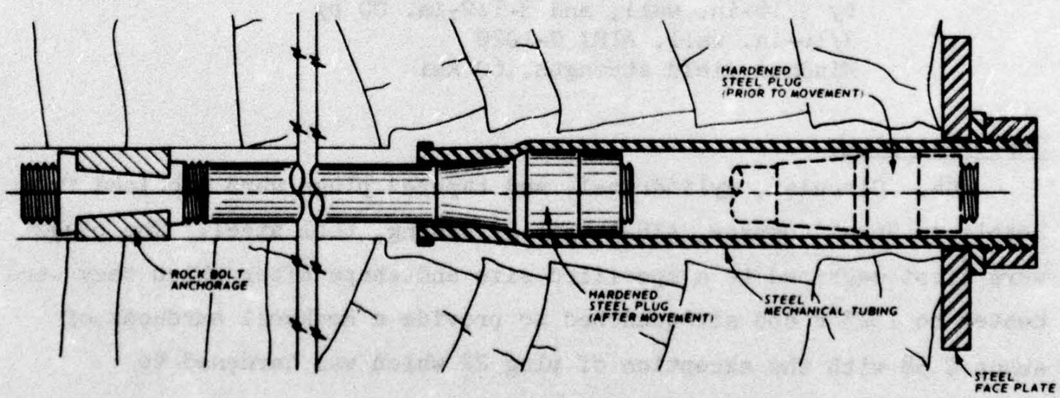


Figure 20. Sketch of in situ Omaha District yieldable rock bolt

mechanism of the yieldable rock bolt is contingent on the frictional force developed, as well as the force required to bend and circumferentially stretch the walls of the metal tube. The latter force is a function of the steepness of the cone bending angle, the number of bends imposed on the tube wall, and the magnitude of the tube expansion.

Developmental Testing

62. The developmental testing, conducted by the MRDL and reported by Brown,[6] was primarily a materials investigation considering different types of tubing as well as various shapes of expansion plugs.

Steel tubes

63. Two types of steel tubing, mandrel and seamless, were investigated. The use of mandrel drawn tubing was based on the desire for a close-tolerance material in order to eliminate wall thickness as a variable. Seamless tubing was investigated as an alternative to the mandrel tubing because of its lower cost. The properties of the tubing used in this work as provided by the manufacturer were as follows:

Seamless mechanical tubing

Cold drawn, low carbon finish annealed.
2-in. OD by No. 11 BWG, AISI C-1018
Minimum yield strength, 55 ksi

Mandrel drawn tubing

2-in. OD by 1/8-in. wall, 2-1/8-in. OD by 3/16-in. wall, and 3-1/2-in. OD by 3/16-in. wall, AISI C-1020
Minimum yield strength, 60 ksi

Expansion plugs

64. Circular, cylindrical, and tapered plugs were machined from Bethlehem Steel Company, AIR-4, air-hardening, tool steel. The plugs were first machined to a specified size and shape after which they were heated to 1525°F and air-quenched to provide a Rockwell hardness of about C 58 with the exception of plug 22 which was hardened to Rockwell C 40.

Preliminary tests

65. The test program consisted of 29 tests using 14 plug designs. Twenty-four tests were made on a 1-in. rock bolt configuration and 5 on

a 1-3/8-in. rock bolt. The first 3 tests were made principally to observe the manner in which metal tubes would be deformed and to provide an early indication of the most desirable plug shape. All tests were directed toward the determination of the load necessary to expand a given size of tubing and the design of a plug which would require 25 kips to expand the tube in the 1-in.-diam (rock bolt) bar assembly and 60 kips in the 1-3/8-in.-diam bar assembly.

66. Two test arrangements were employed. Test assembly No. 1, Figure 21, was used for all but 2 tests (Tests 6-M-2 and 11-M-2, Table 4) in this work. This assembly, which loads the metal tube in compression, was chosen principally for convenience in testing and did not conform exactly to the envisioned prototype shown in Figure 22. In the configuration shown in Figure 21 the steel tube was mounted directly on the movable (upper) crosshead of a Riehle 200,000-lb-capacity universal hydraulic testing machine, with the test bar gripped in the lower or fixed head. The tube was subjected to compressive stresses while the plug was drawn through. Although this condition only approximates the prototype condition, it was considered adequate for this preliminary phase of the work.

67. Test assembly No. 2, Figure 23, more closely simulated the prototype condition. The load was carried in tension in the metal tube. In constructing this assembly, the steel tube was first preformed (using test assembly No. 1) and then welded to the support tube as shown in Figure 23. As stated earlier, only 2 tests were made under this condition. The results of these 2 tests, as will be discussed later, seem to indicate a reasonable relationship between the two test configurations and seem to indicate more closely what might be expected under the prototype loading condition.

68. During the tests, loads were applied at various displacement rates which were previously determined under no-load conditions. During each test, the displacement rate was increased in increments and the total load necessary to draw the plug through the tube was recorded as shown in Tables 4 and 5. It should be noted that the displacement rate under load may be considerably less than that indicated by the machine

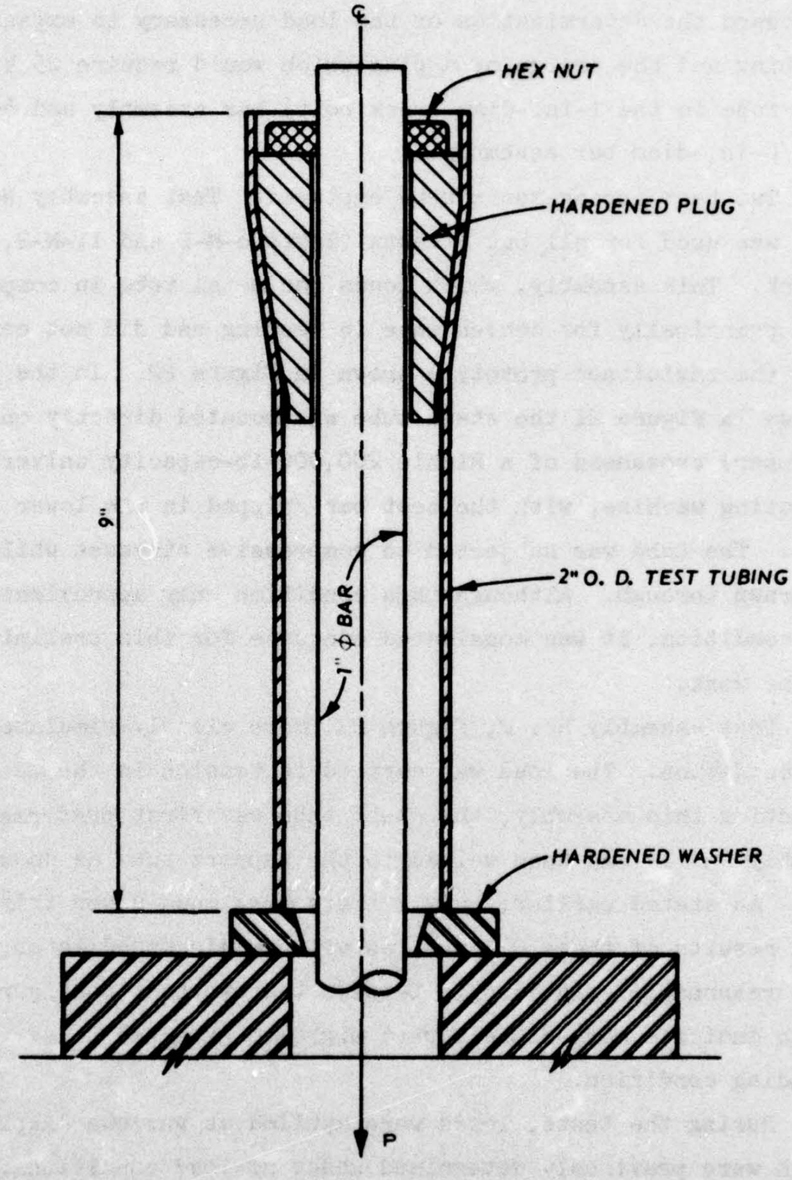


Figure 21. MRDL test assembly No. 1

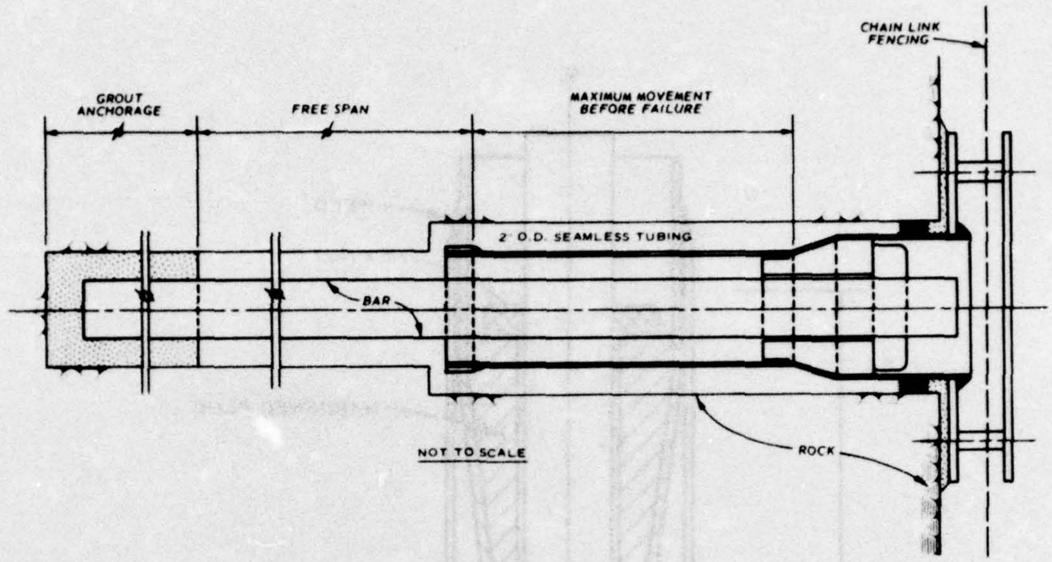


Figure 22. MRDL proposed yieldable rock bolt assembly

setting established for the no-load condition.

69. Table 4 shows results of tests of the 1-in.-diam bar assemblies. Similar data are shown in Table 5 for the 1-3/8-in. bar.

Preliminary evaluation

70. As previously stated, the first 3 tests (tests 1-S1-1, 2-S1-1, and 3-M-1) were made to determine the most desirable plug shape. The first 2 tests employed a cylindrical plug with a rounded fillet at the lower end similar to that shown in Figure 24a. These plugs caused the tube to deform irregularly as shown in the figure. This deformation was the result of the tendency of the plugs to seek the weakest, thinnest point in the tube wall as it was pulled through the tube. Plug 3 was machined similar to plugs 1 and 2 except that it had, in addition, a 1/2-in.-long straight guide at the lower end just below the rounded fillet. As a result, plug 3 produced a straighter, more uniformly expanded tube but required a high peak load for initial penetration into the tube. The high peak initial penetration load was reduced for all subsequent plugs by replacing the rounded fillet section with a tapered transition from the guide to maximum plug diameter. A typical plug and expanded tube are shown in Figure 24b.

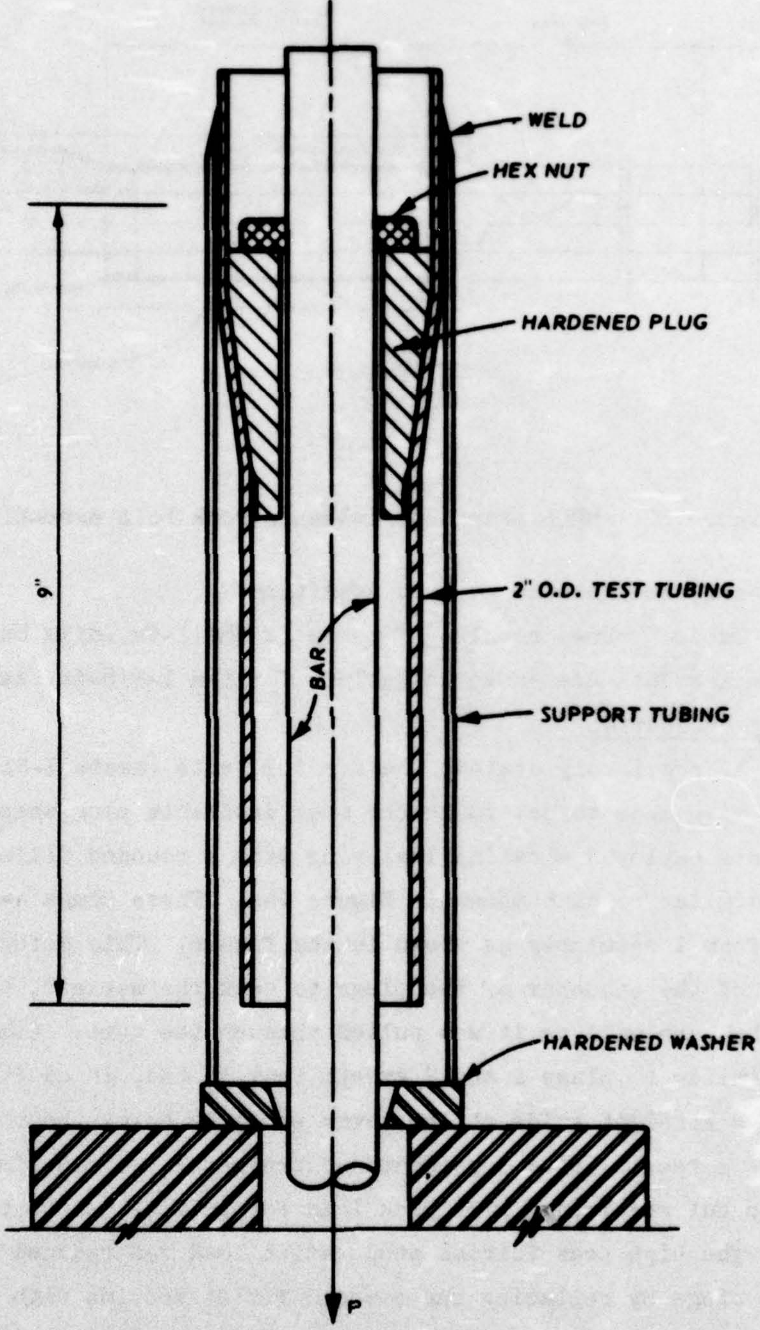


Figure 23. MRDL test assembly No. 2

Table 4

Test Data for 1-In.-Diam Bar

	Test No.											
	1-S1-1	2-S1-1	3-M-1	4-M-1	5-M-1	5-M-1'	5-S-1	5-S-1'	6-M-1	6-M1-1	6-M-2	6-S-1
Plug details												
Plug No.	1	2	3	4	5	5	5	5	6	6	6	6
Maximum plug diam, in.	--	1.9026	1.8494	1.9503	1.9238	1.9238	1.9238	1.9238	1.8992	1.8992	1.8992	1.8992
Plug slope (tangent)	--	--	--	--	0.134	0.134	0.134	0.134	0.112	0.112	0.112	0.112
Initial tube dimensions, in.												
OD	2.0063	2.0061	1.9973	2.0006	2.0002	2.0002	2.0008	2.0014	2.0006	2.1268	2.0006	2.0012
ID (ID_i)	1.8091	1.8089	1.7488	1.7478	1.7482	1.7482	1.7556	1.7558	1.7482	1.7520	1.7482	1.7558
t	0.0986	0.0986	0.1245	0.1264	0.1260	0.1260	0.1226	0.1228	0.1262	0.1874	0.1262	0.1227
t_{min}	0.0969	0.0970	0.1237	0.1242	0.1240	0.1240	0.1218	0.1218	0.1240	0.1848	0.1240	0.1190
Final tube dimensions, in.												
OD	2.1924	2.1079	2.1160	2.2011	2.1799	2.1799	2.1628	2.1625	2.1526	2.2751	2.1404	2.1371
ID (ID_f)	1.9974	1.9137	1.8728	1.9603	1.9375	1.9375	1.9276	1.9265	1.9096	1.9081	1.9010	1.8989
t	0.0975	0.0971	0.1216	0.1204	0.1212	0.1212	0.1176	0.1180	0.1215	0.1835	0.1197	0.1191
t_{min}	0.0957	0.0951	0.1200	0.1185	0.1192	0.1192	0.1170	0.1158	0.1193	0.1808	0.1178	0.1153
Load in kips at indicated displacement velocity												
0.1 in./min	--	7.20	10.75	12.40	13.25	--	6.00	--	10.40	45.00	--	--
0.2	7.50	9.30	11.00	11.70	12.25	11.70	16.00	19.30	10.20	--	13.70	20.10
0.4	10.00	11.00	11.75	11.90	12.40	11.70	15.30	15.80	10.50	31.00	12.50	17.50
1.0	--	11.25	--	12.25	12.40	11.80	16.00	15.80	10.70	30.00	12.80	16.80
1.5	--	12.30	--	--	13.70	--	16.20	16.00	10.75	--	--	16.90
2.0	--	11.35	--	--	--	--	16.40	16.20	--	--	--	17.10

	Test No.											
	6-S-1'	7-M-1	7-S-1	8-M-1	8-M-1'	9-M-1	10-M-1	11-M-1	11-M-1'	11-M-2	11-S-1	11-S-1'
Plug details												
Plug No.	6	7	7	8	8	9	10	11	11	11	11	11
Maximum plug diameter, in.	1.8992	1.9969	1.9969	1.9442	1.9442	1.9903	1.9311	2.1682	2.1682	2.1682	2.1682	2.1682
Plug slope (tangent)	0.112	0.164	0.164	0.226	0.226	0.113	0.122	0.129	0.129	0.129	0.129	0.129
Initial tube dimensions, in.												
OD	2.0011	2.0005	2.0013	2.0006	2.0005	2.0006	2.0005	2.0004	2.0004	2.0004	2.0017	2.0013
ID (ID_i)	1.7557	1.7483	1.7561	1.7480	1.7483	1.7480	1.7481	1.7480	1.7478	1.7480	1.7561	1.7561
t	0.1227	0.1261	0.1226	0.1263	0.1261	0.1263	0.1262	0.1262	0.1263	0.1262	0.1228	0.1226
t_{min}	0.1192	0.1241	0.1218	0.1241	0.1242	0.1147	0.1234	0.1249	0.1236	0.1249	0.1218	0.1218
Final tube dimensions, in.												
OD	2.1377	2.2510	2.2391	2.2139	2.2126	2.2396	2.1829	2.4195	2.4211	2.4061	--	2.4082
ID (ID_f)	1.8983	2.0120	2.0059	1.9727	1.9718	1.9992	1.9407	2.1845	2.1841	2.1753	--	2.1796
t	0.1197	0.1195	0.1166	0.1206	0.1205	0.1202	0.1211	0.1175	0.1185	0.1154	--	0.1143
t_{min}	0.1171	0.1175	0.1160	0.1181	0.1182	0.1179	0.1178	0.1127	0.1099	0.1102	--	0.1111
Load in kips at indicated displacement velocity												
0.1 in./min	--	15.20	--	12.80	12.90	--	--	--	--	--	--	37.70
0.2	--	15.60	22.80	13.80	13.20	15.20	13.00	22.60	--	--	--	39.10
0.4	15.70	15.70	21.70	13.90	13.30	16.25	13.70	23.60	24.80	34.00	31.50	39.50
1.0	--	15.90	21.50	14.00	13.30	16.60	13.40	23.70	--	35.30	Split	--
1.5	--	16.00	21.50	14.10	13.40	17.10	13.20	--	--	Split	--	--
2.0	--	15.75	21.50	14.20	13.50	18.50	13.10	--	--	--	--	--

Note: See Table 5 for test number code.

Table 5

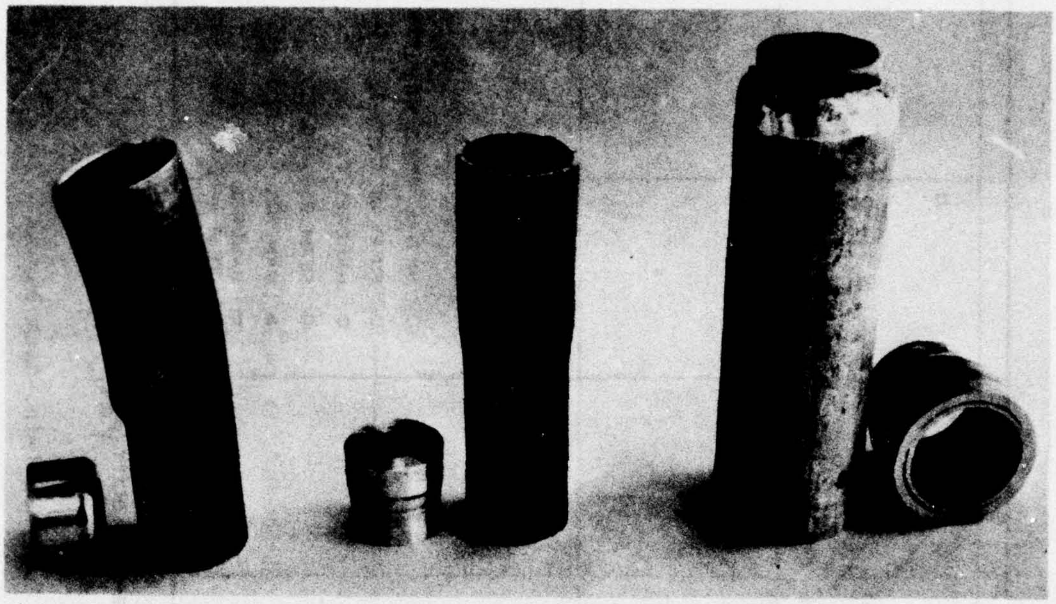
Test Data for 1-3/8-In.-Diam Bar

	Test No.				
	20-S2-1	20-S2-1'	21-S2-1	22-S2-1	22-S2-1'
Plug details					
Plug No.	20	20	21	22	22
Maximum plug diameter, in.	3.3482	3.3478	3.9878	3.5255	3.5255
Plug slope (tangent)	0.038	0.140	0.140	0.068	0.068
Initial tube dimensions, in.					
OD	3.5060	3.5048	3.5060	3.5052	3.5052
ID (ID_i)	3.1208	3.1192	3.1204	3.1210	3.1218
t	0.1926	0.1928	0.1928	0.1921	0.1917
t_{min}	0.1898	0.1850	0.1862	0.1839	0.1878
Final tube dimensions, in.					
OD	3.7478	3.7466	--	3.9178	3.9159
ID (ID_f)	3.3764	3.3758	--	3.5520	3.5503
t	0.1857	0.1854	--	0.1829	0.1828
t_{min}	0.1820	0.1770	--	0.1746	0.1761
Load in kips at indicated displacement velocity					
0.1 in./min	34.40	36.70	64.80	52.00	56.00
0.2	36.30	39.00	Split	55.80	60.20
0.4	39.80	40.20	--	60.10	61.60
1.0	41.40	41.30	--	63.20	63.20
1.5	41.70	41.50	--	64.20	63.00
2.0	41.50	41.80	--	64.60	61.80

Note: Test number code is as follows: First symbol indicates plug number. Second symbol indicates tube type and normal size, i.e.,

Symbol	Tube Type	Average Wall Thickness, in.	Outside Diam, in.
M	Mandrel	0.1262	2
M1	Mandrel	0.1875	2-1/8
S	Seamless	0.1226	2
S1	Seamless	0.0986	2
S2	Seamless	0.1925	3-1/2

Third symbol indicates test assembly, 1 as in Figure 21 and 2 as in Figure 23. The prime symbol (') indicates a second or check test.



a. b. c.

a. TUBE AND PLUG OF TYPE USED IN TESTS 1-S1-1 AND 2-S1-1. NOTE IRREGULARLY DEFORMED AND EXPANDED TUBE.
b. TYPICAL PLUG AND EXPANDED TUBE, TEST ASSEMBLY NO. 1.
c. TEST ASSEMBLY NO. 2. SECTION END VIEW IS AT RIGHT.

Figure 24. Typical plugs and expanded tubes

71. Preliminary data analysis indicated several factors contributing to the load-carrying capacity of a given tube-plug combination. Among these were the ratio of final to initial inside tube diameters (ID_f/ID_i), displacement rate, friction coefficient between plug and tube wall, and the tube wall thickness. The effect of tubing yield point stress could be significant, but was not separated in the data analysis.

72. Figures 25 and 26, derived from the data presented in Tables 4 and 5, seem to indicate that the ratio of the final to the initial internal diameter is the major variable governing load capacity for a given tube size. Data points deviating from these curves are believed to be the result of variations in friction coefficients and the amount of internal tube surface abrasion during tests. In all cases, immediately

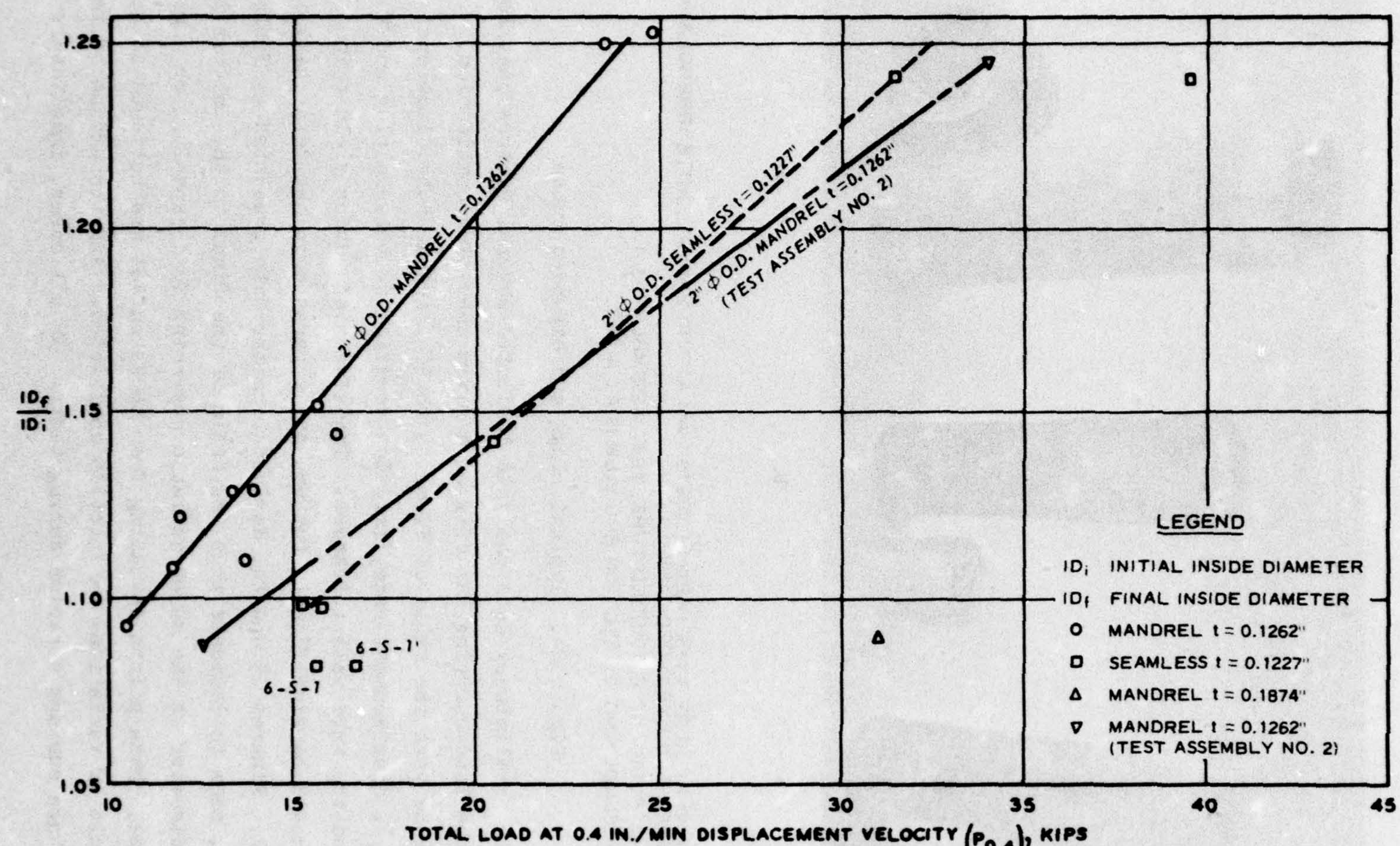


Figure 25. Load versus ratio ID_f/ID_i for MRDL 1-in.-diam bar

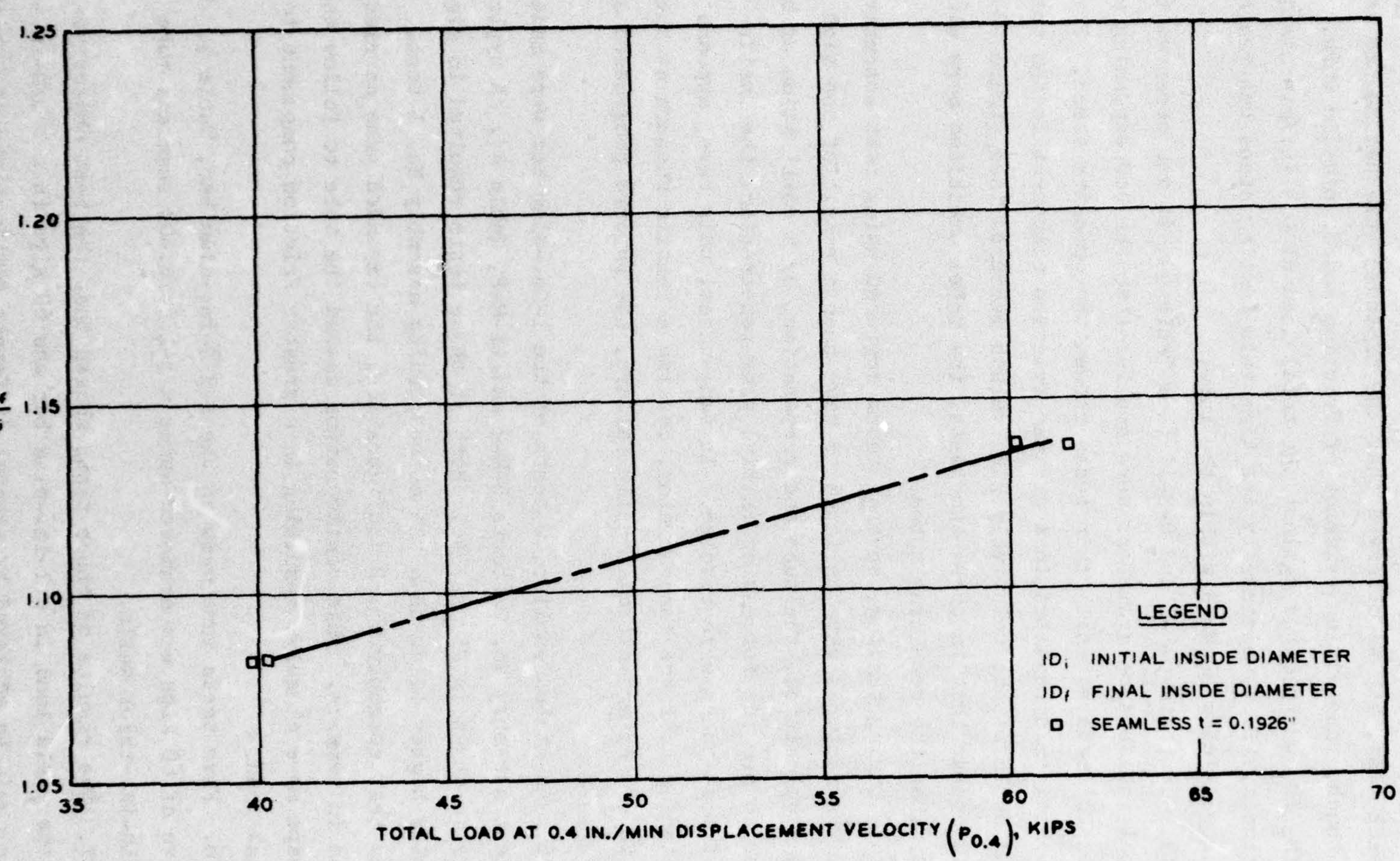


Figure 26. Load versus ratio ID_f/ID_i for MRDL 1-3/8-in.-diam bar

after each test, it was observed that the expanded tube had become warm to the touch, thus giving evidence of friction and/or plastic work. The ratio ID_f/ID_i was plotted against the total load at 0.4-in./min displacement velocity ($P_{0.4}$) because by the time this testing speed was reached, the plug was fully engaged within the tube.

73. In tests 6-S-1 and 6-S-1' (see Table 4), it was observed that the final inside tube diameters were smaller than the corresponding maximum plug diameters. All other tests showed the opposite trend. For these tests, this resulted in a greater friction component in the total load and explains the relatively high values measured (see Figure 25). It would appear that in these two tests, the tubes exhibited more elastic recovery than the remaining tubes.

74. During testing, several tubes ruptured using test assembly No. 1. The ruptures were believed to have been a result of the high displacement velocities, the tube end preparation, or a combination of both. In order to provide for easier initial plug penetration, the inside edges of most tubes were beveled. In some cases, this bevel appears to have acted as a stress concentrator, causing a tensile rupture at the end of the tube. After initial tensile failure, the rupture progressed as a shear failure.

75. As stated earlier, 2 tests of the 1-in.-diam bar were made using test assembly No. 2 (tests 6-M-2 and 11-M-2, Table 4). A typical assembly is shown in Figure 24c. Both of these tests resulted in significantly higher loads than the corresponding assembly No. 1 tests. With the test assembly No. 2 configuration, the expanded tube carried the load in tension. This configuration caused the tube to follow the plug shape more closely, resulting in a greater friction component to the total load.

76. Five tests were made on the 1-3/8-in.-diam bar, Table 5. The objective of 60 kips was achieved using a 3-1/2-in.-OD seamless tube with 3/16-in.-thick walls.

77. The results of these tests showed that the test objectives of 25 kips yield load in a 1-in.-diam bar and 60 kips in a 1-3/8-in.-diam bar could be achieved by several different combinations of tubing

types, plug diameters, and test configurations.

Design Testing

78. The final design of the yield mechanism was preceded by 3 additional types of tests which provided a rough guide for the design. The tests were conducted by the Omaha District. The types of tests were designated as: (a) preprototype tests, (b) protoprep tests, and (c) prototype tests, as shown in Figures 27, 28, and 29, respectively.

Test specimens

79. The tubings used as yield mechanisms for these tests were 1-1/4-in. extra strong pipe, butt welded tubing, cold-drawn seamless tubing, and drawn-over-mandrel seamless tubing. The specimens, which were 8 to 11 in. long, were measured for length, wall thickness, inside diameter, and outside diameter both before and after testing. The extra strong pipe inside diameter and wall thickness varied as much as 0.040 and 0.028 in., respectively, at the same cross section. The mechanical tubing dimensions were within 0.007 in. of catalog nominal dimensions.

80. The expansion plugs were designed to expand the tubes in two stages. A small bending angle (2 deg) first expands the tube gradually beyond the yield point and then steeper bending angles expand the tube more abruptly in the plastic zone. An exception to this was the use of a 10-deg expansion angle for the initial expansion of 2 tubes during prototype testing. A schematic drawing and definitions of plug nomenclature as used by the Omaha District are provided in Figure 30.

81. A separate plug section was machined for each expansion angle. The use of separate sections permitted the assembly of various combinations of bending angles without the necessity of machining a different expansion plug for each combination. The plugs were replaced when excessive wear or distortion was noted. The material from which the expansion plugs were machined was Bethlehem Steel Company, AIR-4, air-hardening, tool steel and had a Rockwell hardness of B 85.

82. In an effort to minimize or at least stabilize frictional resistance at the plug-tube contact, the insides of the tubes (with the

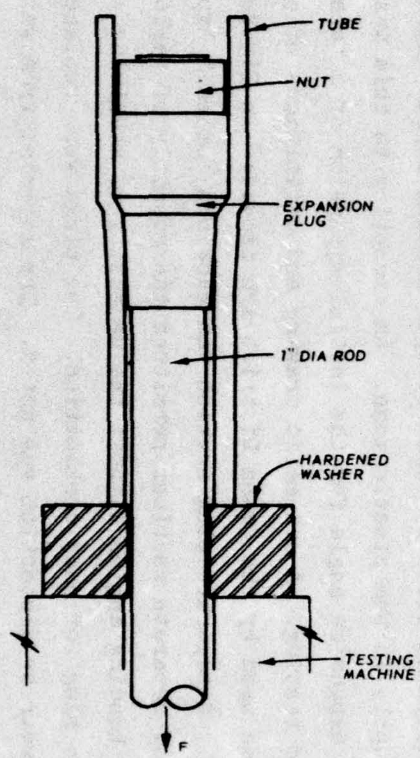


Figure 27. Omaha District pre-prototype testing assembly

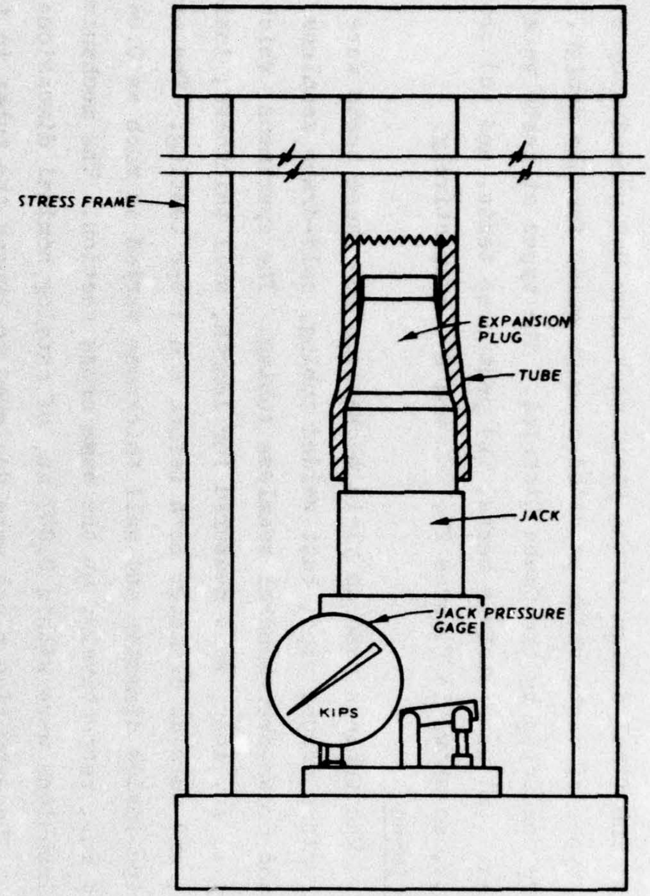


Figure 28. Omaha District protoprep testing assembly

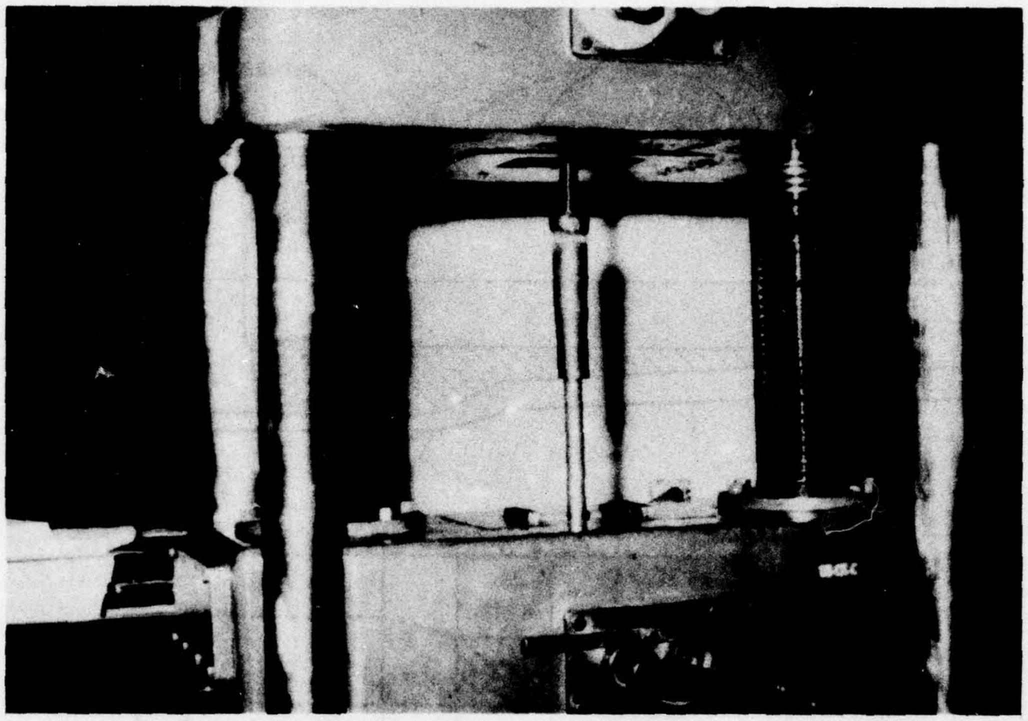


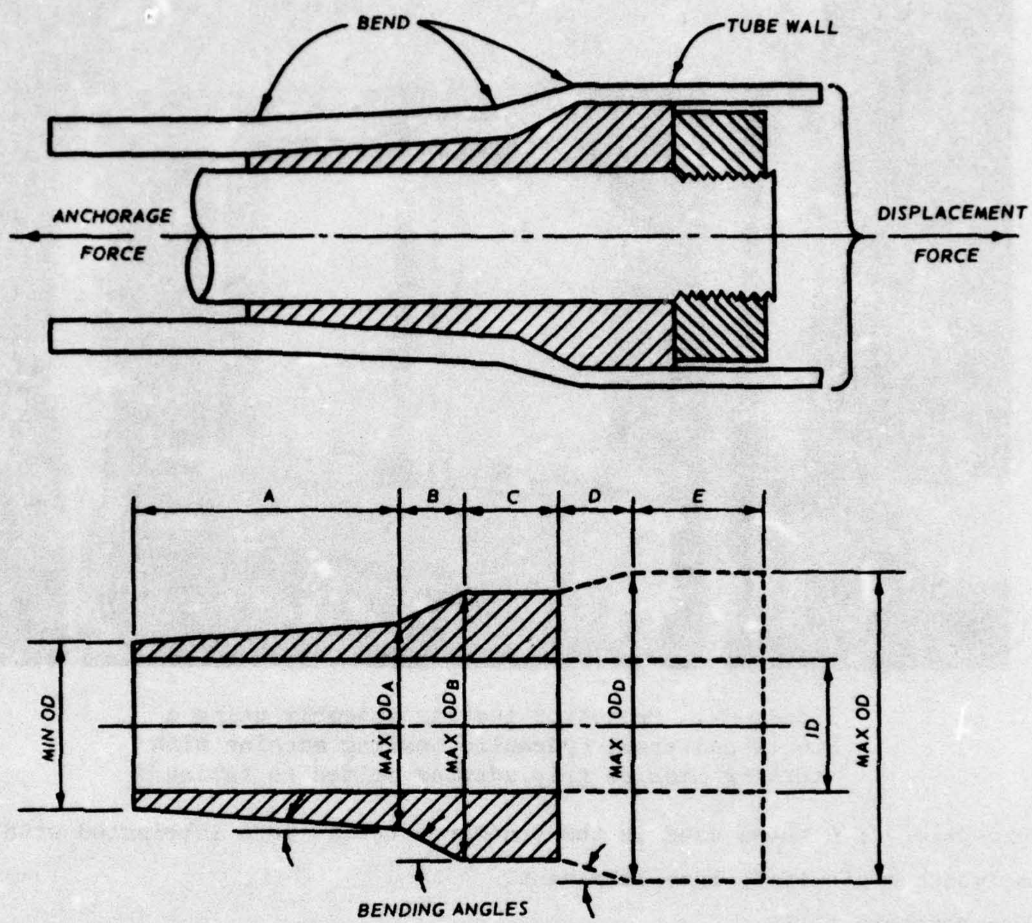
Figure 29. Prototype testing assembly using a Riehle universal hydraulic testing machine with testing machine grip adapter welded to tubing

exception of 2 tubes used in the protoprep tests) were lubricated with a molybdenum disulfide base lubricant.

Preprototype tests

83. The initial studies were performed by the Omaha District on the simple and easily fabricated configurations designated preprototype tests, as shown in Figure 27. The studies were oriented primarily toward expansion plug design and tube response to expansion.

84. The yield mechanism was set up so that the load would be carried in compression in the tube. The tests were conducted utilizing a Riehle 200,000-lb-capacity universal hydraulic testing machine. Seamless cold-drawn mechanical tubing, 1-1/4-in. extra strong pipe, and drawn-over-mandrel welded mechanical tubing were expanded with numerous plugs possessing different expansion angles. Results of the tests are given in Table 6. The yield forces presented in the table are maximums



CROSS SECTION OF TUBE AND PLUG

PLUGS ARE DESCRIBED FROM THE MINIMUM TO THE MAXIMUM OUTSIDE DIAMETER IN TERMS OF THE BENDING ANGLE AND THE MAXIMUM OUTSIDE DIAMETER FOR EACH TAPERED SECTION (A,B,D, ETC) AND SIMPLY BY THE LENGTH IN INCHES FOR THE FLAT SECTIONS. FOR EXAMPLE, A PLUG WITH THE TYPICAL CROSS SECTION WHICH INCLUDES SECTIONS A THROUGH C ABOVE MIGHT BE DENOTED AS:

$$\frac{2^\circ}{1.100} \quad \frac{15^\circ}{1.160} \quad 0.5$$

WHEREAS A PLUG WITH THE CROSS SECTION WHICH INCLUDES SECTIONS A THROUGH E ABOVE MIGHT BE DENOTED AS:

$$\frac{2^\circ}{1.100} \quad \frac{15^\circ}{1.160} \quad 0.5 \quad \frac{10^\circ}{1.200} \quad 0.75$$

Figure 30. Schematic and nomenclature of Omaha District yielding plug

Table 6

Test Data for Preprototype Tests

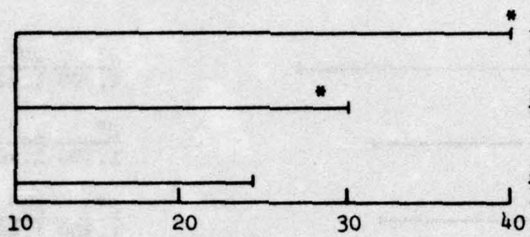
Tube Wall Thickness / Tube ID in.	Tube No.	Yield Load, kips	Plug Dimension Nomenclature (Figure 30)
1-1/4-Inch Extra Strong Pipe			
0.193 / 1.275	1_2		2°/1.300 20°/1.400 1.5 20°/1.500 0.5
0.192 / 1.282	2_2		2°/1.300 15°/1.400 1.5 20°/1.500 0.5
0.198 / 1.260	6_2		2°/1.300 20°/1.400 1.5 15°/1.500 0.5
0.190 / 1.289	B_2		2°/1.300 15°/1.400 1.5 15°/1.500 0.5
0.196 / 1.263	5_2		2°/1.300 10°/1.400 1.5 10°/1.500 0.5
0.192 / 1.282	2		2°/1.400 10°/1.500 0.5
0.193 / 1.275	1		2°/1.400 5°/1.500 0.5
0.196 / 1.261	5		2°/1.400 10°/1.450 0.25 10°/1.500 0.5
0.198 / 1.260	6		2°/1.400 10°/1.450 0.25 10°/1.500 0.5
0.195 / NM	A		2°/1.400
0.194 / NM	B		2°/1.400 2°/1.487
0.196 / 1.280	8		2°/1.300 15°/1.400
0.197 / 1.270	7	Split	2°/1.300 15°/1.400 0.5 15°/1.500 0.5
0.196 / 1.280	8_2	Split	2°/1.300 15°/1.400 0.5 15°/1.500 0.5

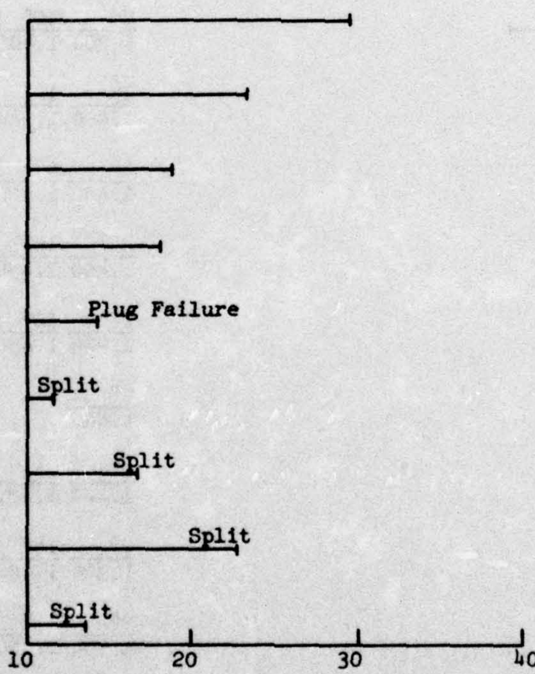
(Continued)

Note: Yield loads measured at a displacement rate of 0.4 in./min.

Table 6 (Concluded)

Tube Wall Thickness / Tube ID in.	Tube No.	Yield Load, kips	Plug Dimension Nomenclature (Figure 30)
Seamless Cold-Drawn Mechanical Tubing			
0.250/1.250	11_1	*	2°/1.300 10°/1.400 1.5 10°/1.500 0.5
0.250/1.250	12	*	2°/1.300 10°/1.500 0.5
0.250/1.250	11_2		2°/1.400 0.5
Drawn-Over-Mandrel Welded Mechanical Tubing			
0.190/1.250	10_2		2°/1.300 20°/1.400 1.5 20°/1.500 0.5
0.190/1.250	18		2°/1.400 0.5
0.190/1.250	9_1		2°/1.300 15°/1.400 0.5
0.190/1.250	10		2°/1.300 15°/1.400 0.5
0.190/1.250	9_2	Plug Failure	2°/1.300 20°/1.400 0.5
0.190/1.250	3	Split	2°/1.400 5°/1.500 0.5
0.190/1.250	4	Split	2°/1.400 5°/1.500 0.5
0.190/1.250	19	Split	2°/1.400 0.5
0.380/1.250	17	Split	2°/1.400 0.5





* Test discontinued before a maximum was indicated.

for a 0.4-in./min displacement rate. Splitting seemed to occur where low-expansion-angle plugs were used. The yield forces appeared to be critically dependent on plug geometry but relatively consistent for the same geometry.

Protoprep tests

85. The protoprep tests were performed during the expansion of the tube ends to permit the assembly of the prototype yielding mechanisms. A frame and hydraulic jack equipped with a pressure gage were used to force the expansion plugs the necessary distance into the tubes as shown in Figure 28.

86. The tubing types tested were seamless cold-drawn, butt welded, and drawn-over-mandrel welded. The tubes were expanded with numerous expansion plugs consisting of various combinations of expansion angles. The results of the protoprep tests are presented in Table 7. Again the yield forces were influenced to a large extent by plug geometry. It was also determined, by the omission of lubricant on two of the tests, that the molybdenum disulfide grease reduces the yield force by about one-third. The frictional component of the yield force thus appears to be approximately the same for both the Omaha District and South African yieldable rock bolts.

Prototype tests

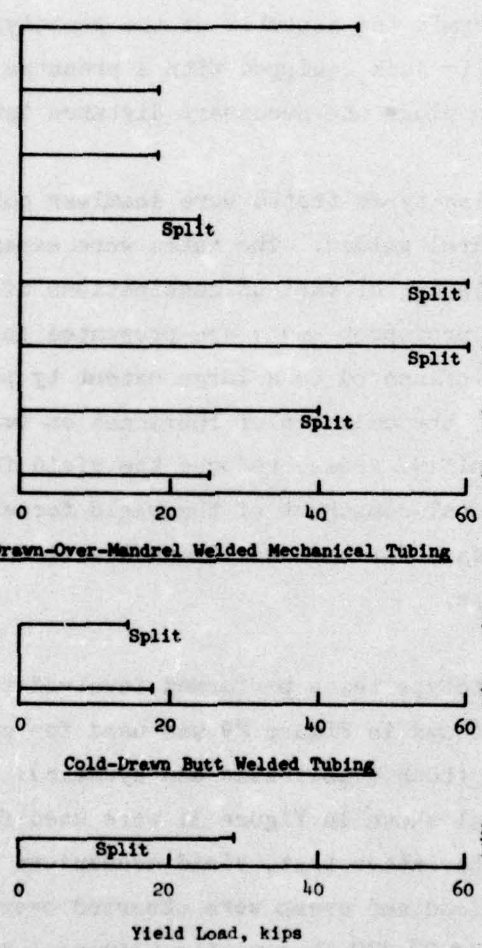
87. The prototype tests performed involved two types of loading. The configuration shown in Figure 29 was used for constant-rate-of-displacement tests (both quasistatic and dynamic). The loading frame and creep measuring dial shown in Figure 31 were used for creep and relaxation tests. For the latter test, yield mechanisms were loaded to a given level and loss of load and creep were observed over a period of time.

88. A Riehle 200,000-lb-capacity universal testing machine was used for both the quasistatic and the dynamic tests. The machine was equipped to apply tensile forces to the yield mechanisms via adapters which were either threaded to or welded on the tubes as determined by their diameters. The yield forces developed at a displacement rate of 0.4 in./min for various combinations of tube and expansion plug designs are presented in Table 8.

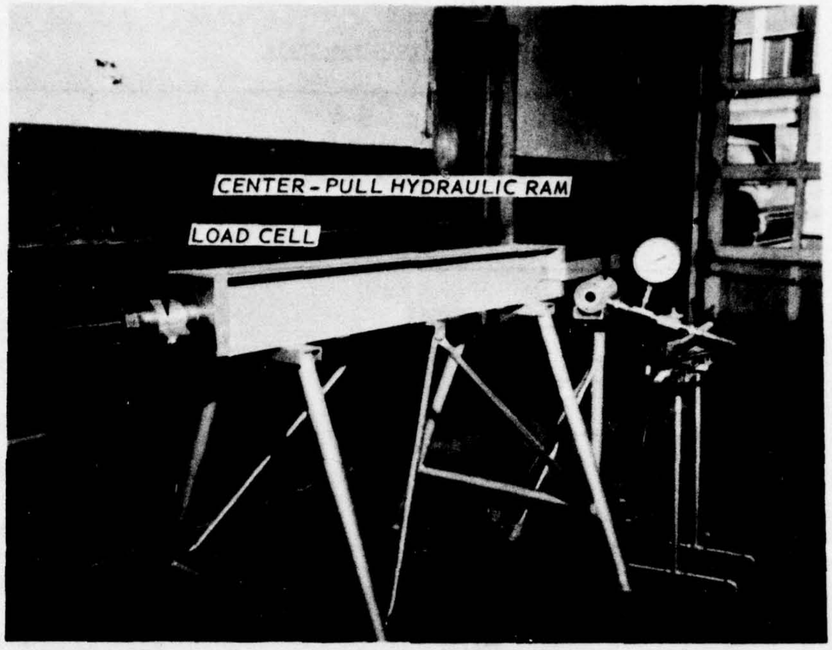
Table 7

Test Data for Protoprep Tests

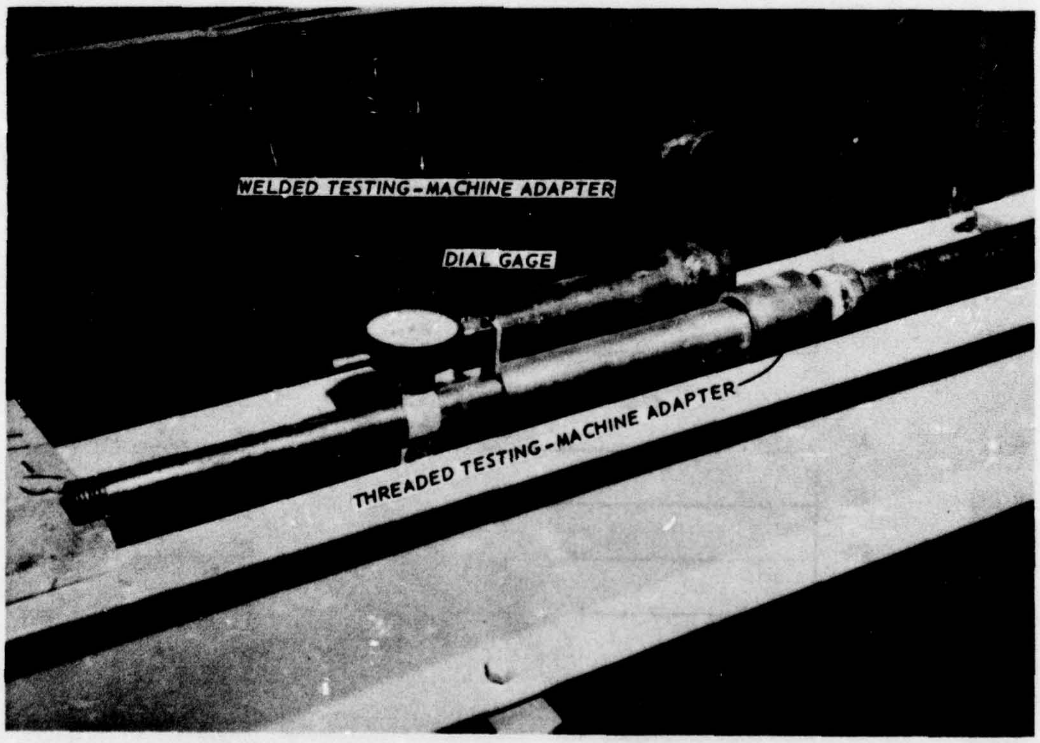
Tube Wall Thickness / Tube ID, in.	Tube No.	Lubricant	Yield Load, kips	Plug Dimension Nomenclature (Figure 30)
Seamless Cold-Drawn Mechanical Tubing				
0.188/1.375	20_B	Moly*		2°/1.400 0.5 2°/1.500 2°/1.600 0.5
0.188/1.375	21	Moly		2°/1.400 0.5 2°/1.500
0.188/1.375	22	Moly		2°/1.400 0.5 2°/1.500
0.219/1.062	50	Moly	Split	2°/1.100 15°/1.185 1.5 15°/1.210 1.5
0.219/1.062	50.1	None	Split	2°/1.100 2°/1.210 0.5
0.219/1.062	50.2	None	Split	2°/1.100 2°/1.210 0.5
0.219/1.062	50.3	Moly	Split	2°/1.100 2°/1.210 0.5
0.219/1.062	51 thru 62	Moly		2°/1.100 15°/1.185 1.5 15°/1.210 1.5
Drawn-Over-Mandrel Welded Mechanical Tubing				
0.188/1.375	26	Moly	Split	2°/1.400 0.5 2°/1.500 2°/1.600 0.5
0.188/1.375	27	Moly		2°/1.400 0.5 2°/1.500
Cold-Drawn Butt Welded Tubing				
0.188/1.375	23	Moly	Split	2°/1.400 0.5 2°/1.500 2°/1.600 0.5



* Molybdenum disulfide grease lubricant.



a. Hydraulic loading frame



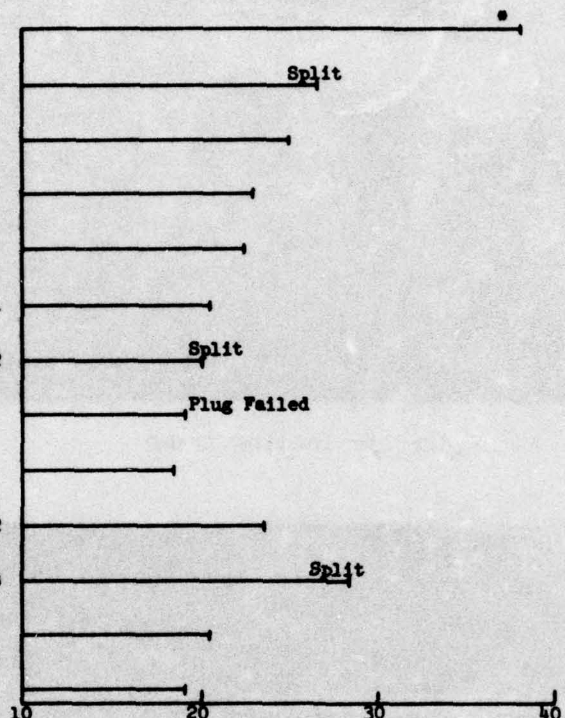
b. Measurement system

Figure 31. Omaha District creep and relaxation measuring assembly

Table 8

Test Data for Prototype Tests

Seamless Cold-Drawn Mechanical Tubing

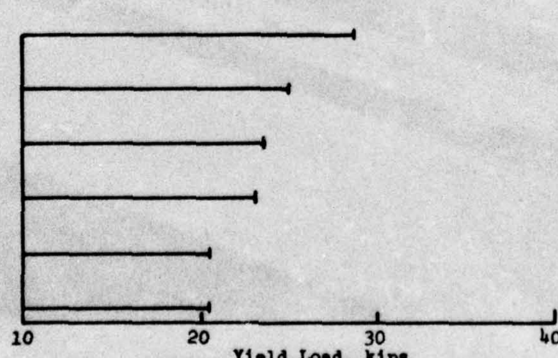


Tube Wall Thickness / Tube ID, in.	Tube No.	Yield Load, kips	Plug Dimension Nomenclature (Figure 30)
0.219 / 1.062	58	*	2°/1.100 15°/1.149 1.0 15°/1.200 1.0
0.219 / 1.062	52	Split	2°/1.100 1.0 2°/1.200
0.219 / 1.062	53		2°/1.100 15°/1.150 1.0 15°/1.200 1.0
0.219 / 1.062	56		2°/1.100 15°/1.150 1.0 15°/1.190 1.1
0.219 / 1.062	55		2°/1.100 15°/1.150 1.0 15°/1.190 1.1
0.219 / 1.062	58_1		2°/1.100 15°/1.150 1.0
0.219 / 1.062	51_2	Split	2°/1.100 2°/1.200 1.0
0.219 / 1.062	57	Plug Failed	2°/1.100 15°/1.200 1.0
0.219 / 1.062	54		2°/1.100 15°/1.150 1.0
0.250 / 1.250	11_2		2°/1.400
0.188 / 1.375	20_B	Split	2°/1.400 0.5 2°/1.500 10°/1.600 0.5
0.188 / 1.375	22		10°/1.400 1.5 20°/1.500 0.5
0.188 / 1.375	21		2°/1.300 1.5 20°/1.500 0.5

Drawn-Over-Mandrel Welded Mechanical Tubing

Tube Wall Thickness / Tube ID, in.	Tube No.	Plug Dimension Nomenclature (Figure 30)
0.188 / 1.375	27	10°/1.400 1.5 20°/1.500
0.188 / 1.250	18	2°/1.400 1.5

1-1/4-In. Extra Strong Pipe



Tube Wall Thickness / Tube ID, in.	Tube No.	Plug Dimension Nomenclature (Figure 30)
0.19 / 1.28	2_2	2°/1.300 15°/1.400 1.5 20°/1.500
0.198 / 1.276	22	2°/1.300 15°/1.400 1.0 15°/1.500
0.190 / 1.269	20	2°/1.300 15°/1.500 1.0 15°
0.198 / 1.270	21	2°/1.300 15°/1.400 1.0 15°/1.500
0.193 / 1.275	1_2	2°/1.300 10°/1.400 1.5 10°/1.500
0.193 / 1.260	6_2	2°/1.300 10°/1.400 1.5 15°/1.500

Note: Yield loads measured at a displacement rate of 0.4 in./min.
* Grip adapter failed before a maximum load was indicated.

89. Based upon the results obtained in the preprototype tests, protoprep tests, and the first few prototype tests, a final tube size and expansion plug design were chosen for additional testing. Seamless cold-drawn mechanical tubing with a wall thickness of 0.219 in. and an inside diameter of 1.062 in. expanded with a $\frac{2^\circ}{1.100}\ \frac{15^\circ}{1.150}\ 1.0$ plug (see Figure 30 for plug dimension nomenclature) was the design chosen for the yielding mechanism to develop a yield force of approximately 21 kips. The expansion plug chosen for use was machined from a single piece of Bethlehem Steel Company, AIR-4, air-hardening, tool steel, Rockwell hardness B 85, and then hardened to a Rockwell hardness C 53 by heating it to 1500°F and air-quenching.

90. In the final phase of testing, 2 yieldable rock bolt prototypes produced yield forces varying between 20 and 22 kips while extending approximately 6 in. at rates varying from 0.1 to 1.0 in./min. The results of the tests, along with a plot which demonstrates the effects of displacement rate on yield forces, are shown in Figure 32.

91. Creep and relaxation tests were performed in the loading frame shown in Figure 31 using the final yield mechanism design. A center-pull hydraulic ram was used to tension the yielding mechanism and the loads were monitored with a load cell. The loads were held by a nut tightened against a bearing plate. The prototype yielding mechanism was tested for creep and load loss under different loads in five short tests of 20 to 90 hours duration, and one long test of 35 days duration. Results of the tests are presented in Figures 33 and 34.

Design evaluation

92. The results of the design testing confirmed that the variables affecting the magnitude of resistance of the yielding mechanism are the friction force at the plug-wall contact, the resistance of the tube wall to bending and expansion, the rate of extension, and the magnitude of the applied load.

93. The frictional component of the resistance provided was determined to be influenced by the condition of the plug-wall contact area (lubricated, smooth, wet, dry, rusty, etc.), the normal force at the contact area, and the amount of the contact area. The yield force of a

TUBE DIMENSIONS BEFORE AND AFTER EXTENSION, INCHES

TUBE NO. →	61		62	
	BEFORE	AFTER	BEFORE	AFTER
O.D.	1.505	1.571	1.505	1.569
I.D.	1.062	1.161	1.063	1.161
LENGTH	8.88	9.03	8.88	9.03

EXPANSION PLUG DIMENSIONS

ANGLE NO.	BENDING ANGLE	O.D. MAX INCHES	FLAT INCHES
I	2°	1.100	--
II	15°	1.160	0.5

NOTE: O.D. AND I.D. ARE MEASURED 3/4" FROM THE TUBE END. TUBE AND PLUG LUBRICATED WITH MOLYBDENUM DISULFIDE GREASE.

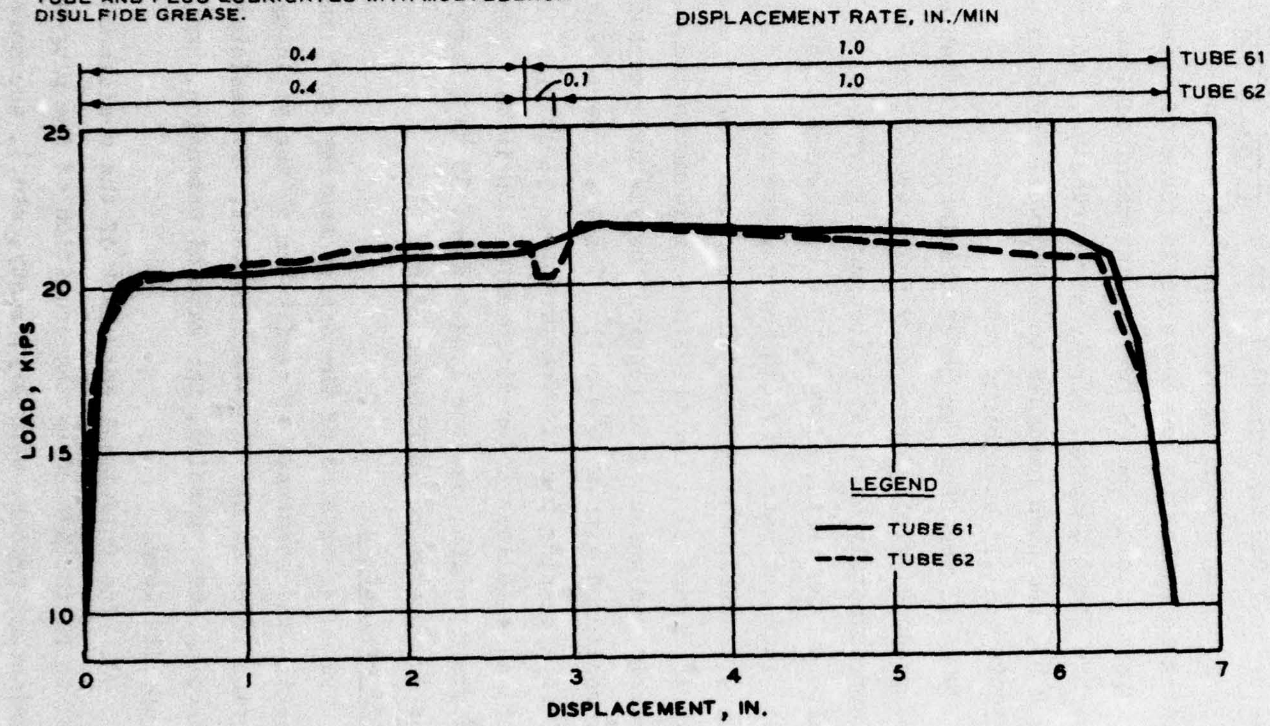
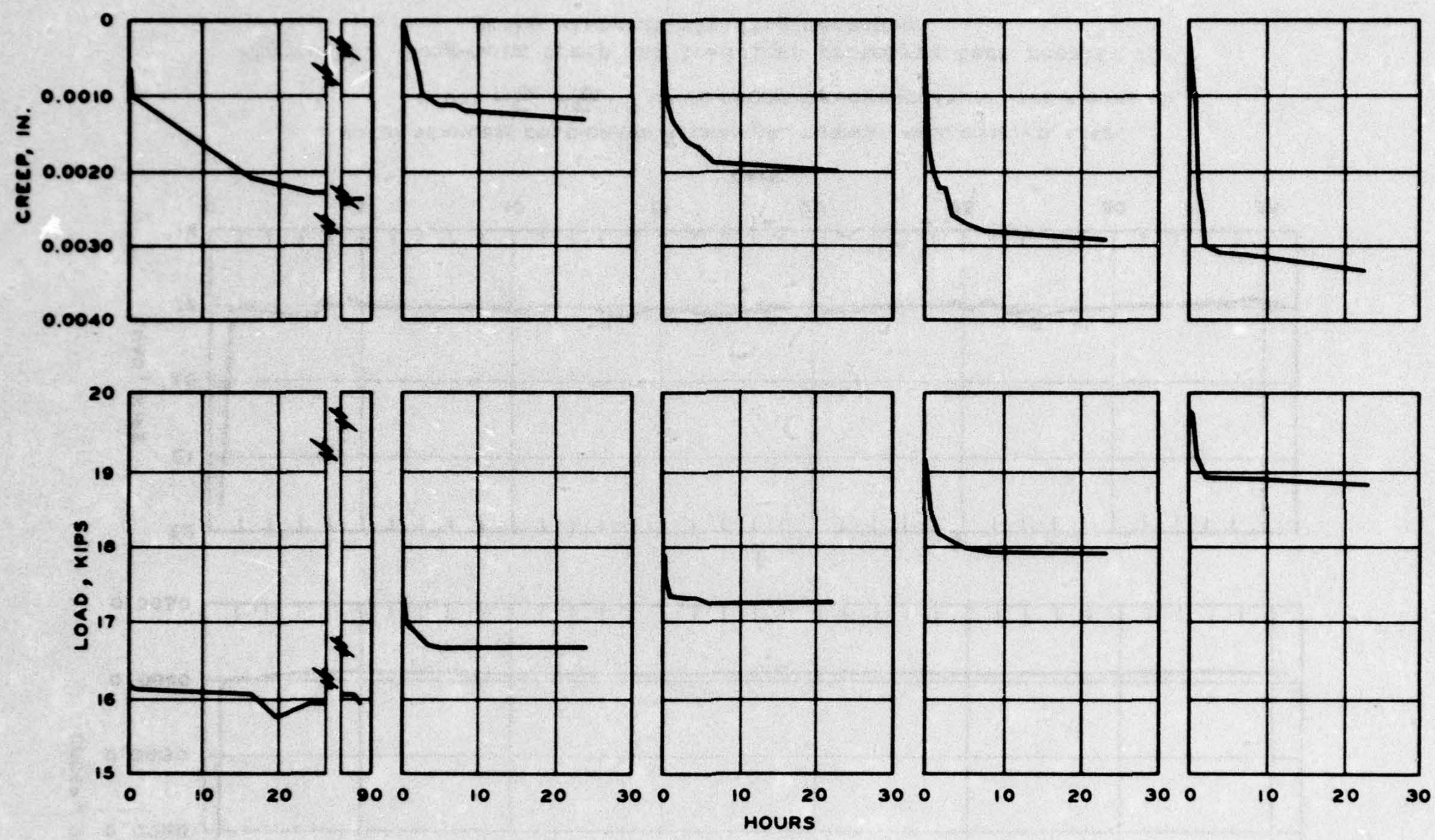


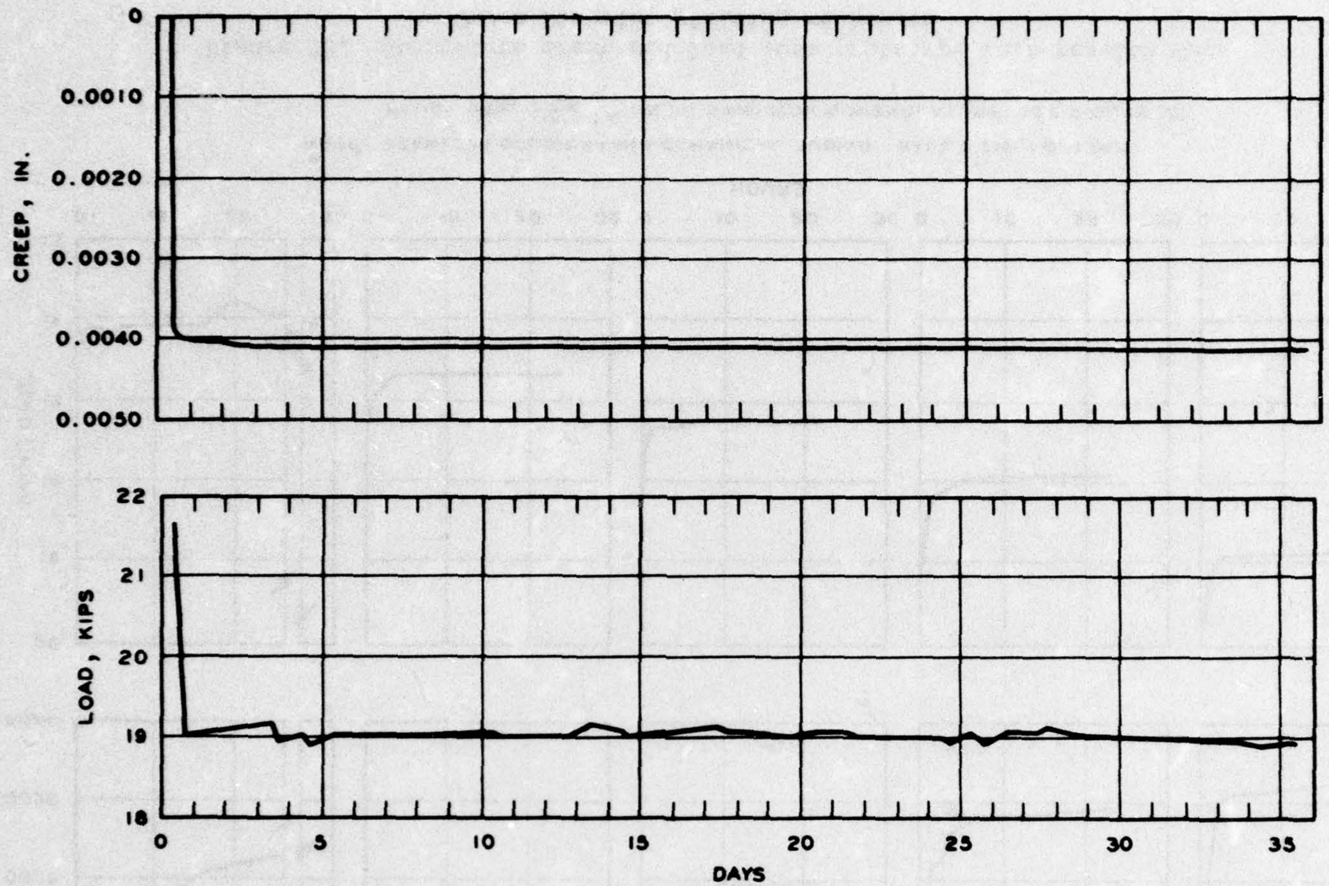
Figure 32. Dynamic test results of Omaha District prototype yieldable rock bolt



NOTE: SEAMLESS COLD-DRAWN MECHANICAL TUBING: WALL 0.219", I.D. 1.062".

PLUG: $\frac{2°}{1.100}$ $\frac{15°}{1.160}$ 1.0 (PLUG DIMENSION NOMENCLATURE - SEE FIGURE 30).

Figure 33. Short-term creep and load loss prototype test results for Omaha District yielding mechanism



NOTE: SEAMLESS COLD-DRAWN MECHANICAL TUBING: WALL 0.219", I.D. 1.062".

PLUG: $\frac{2°}{1.100}$ $\frac{15°}{1.160}$ 1.0 (PLUG DIMENSION NOMENCLATURE - SEE FIGURE 30).

Figure 34. Long-term creep and load loss prototype test results for Omaha District yielding mechanism

lubricated system was found to be approximately 33 percent less than that of a nonlubricated system (Table 7; tubes 50.1 and 50.2). On the other hand, the results tend to indicate that lubrication stabilizes the yield forces by retarding expansion plug wear and diminishing the effects of variable tube surface conditions.

94. Friction at the contact area of the tube wall and the expansion plug is a function of the magnitude of the normal force. The normal force was determined to be governed by the resistance of the tube to expansion, and the tension on the tube. An increase in tension effectively increases the resistance of a tube to expansion, thereby increasing the frictional force by increasing the normal force at the contact area.

95. The amount of contact area provided for frictional resistance is a direct function of the expansion plug bending angle. Expanding the tube with a small bending angle distributes the force over a larger tube area, which tends to average out variable yield forces caused by dimensional variations and/or nonuniform yield points, etc., and increases the resistance caused by friction.

96. For a given degree of tube expansion, the design testing indicated that the yield forces increased as the bending angles increased and as the number of bends was increased. This is generally verified in Tables 6, 7, and 8. For smaller bending angles on the expansion plugs it was determined that the tubing was generally more vulnerable to splitting.

97. Dimension measurements made before and after testing each yielding mechanism indicated a correlation between expansion plug hardness and tube response to expansion. In the first prototype tests, the tubes lengthened and decreased in cross-section area. It was suspected that wear of the softer expansion plug used for the first prototype tests produced a profile that differed from the as-turned profile which was retained by the harder plug used for the final prototype design tests. The tube response is thus affected by the abruptness of the transition from the final bending angle to the flat slope at maximum O.D.

98. Tube cross-section area was computed from diameters measured at 90-deg intervals approximately 3/4 in. from the plug exit end of the

tube. The inside diameter at the exit end of the tubes averaged 0.008 in. less at the end than that at a locus 3/4 in. from the end.

99. Measurements of yield force made under dynamic conditions indicated that the yield force varies slightly as extension rate varies, i.e. 20 kips at 0.1 in./min and 22 kips at 1.0 in./min (Figure 32). Under static conditions, the stabilized yield force increased with increased applied load, i.e. as the initial load was increased, the lower value at which the load stabilized also increased (Figure 33). The increased yield force results because the force required to produce a lateral displacement at some point along a tension member varies with the tensile force. Since the tube was under longitudinal tension between the expanded section and the locus of transition from the original diameter to the expanded diameter, the resistance to outward bending of the tube wall by advancement of the expansion plug increased as the tension on the tube increased. The results were thus a greater normal force at the contact and an increased frictional component of the yield force.

Final Laboratory Tests

100. In an effort to evaluate completely the yielding mechanism utilized for the Omaha District yieldable rock bolt, additional pull tests were performed by LLL for WES. The testing, reported by Tatro (Appendix A of this report), was performed concurrently with the tests performed on the Bureau of Mines yieldable rock bolts which were previously described.

Testing program

101. The same testing program was used as that described for the Bureau of Mines yieldable rock bolt. The program was conducted in three phases: a quasistatic load test run at a slow strain rate (0.017 in./sec), low-velocity dynamic tests run at a strain rate of 1.390 in./sec, and high-velocity dynamic tests run at strain rates between 14.567 and 29.921 in./sec. A total of five yielding mechanisms were tested, with one quasistatic test, two low-velocity tests, and two high-velocity tests being performed. The dynamic tests were run to displacements of 3.461 to 4.291 in. while the quasistatic test was run to a displacement

of 7.000 in. Data were recorded in terms of force and displacement.

102. The quasistatic test was performed on a 112.4-kip (500-kN), closed-loop, servo-controlled test machine, and standard load and deformation measurements were made. The yielding mechanism was tested at a constant rate of 0.017 in./sec and the results in terms of load versus displacement are shown in Figure 35.

103. The two low-velocity tests were also performed on the closed-loop, servo-controlled test machine. As with the Bureau of Mines rock bolt, the displacement velocity (1.390 in./sec) was outside the rating of the test machine but was verified by auxiliary measurements. Results of both of the low-velocity tests in terms of load versus displacement are shown in Figure 36.

104. The high-velocity tests were performed at LLL's hydraulic shaker facility and the procedures, equipment, and instrumentation were the same as previously described for the Bureau of Mines rock bolt tests. Results of the two tests in terms of load versus displacement are shown in Figures 37 and 38. Constant rates of displacement were not achieved during the tests and, therefore, measurements of displacement rates versus time were recorded. These measurements, as well as load versus time and displacement versus time, are presented in Appendix A (LLL's final report on the laboratory test results).

Final test results

105. The results of the final pull tests performed on the Omaha District rock bolts are summarized in Table 9. The results indicate a slight decrease in load capacity with increases in displacement rates. However, as previously determined for the Bureau of Mines rock bolts, the closeness of the quasistatic and low-velocity test results indicates that the effect of displacement rate on load capacity is not realized unless the velocities exceed 1.390 in./sec (the low-velocity displacement rate).

106. The high-velocity tests yielded dynamic records of a much better quality than those obtained with the Bureau of Mines rock bolts. The load-displacement curves were much smoother and load fluctuations were much less severe. Additionally, yielding was not noted in the

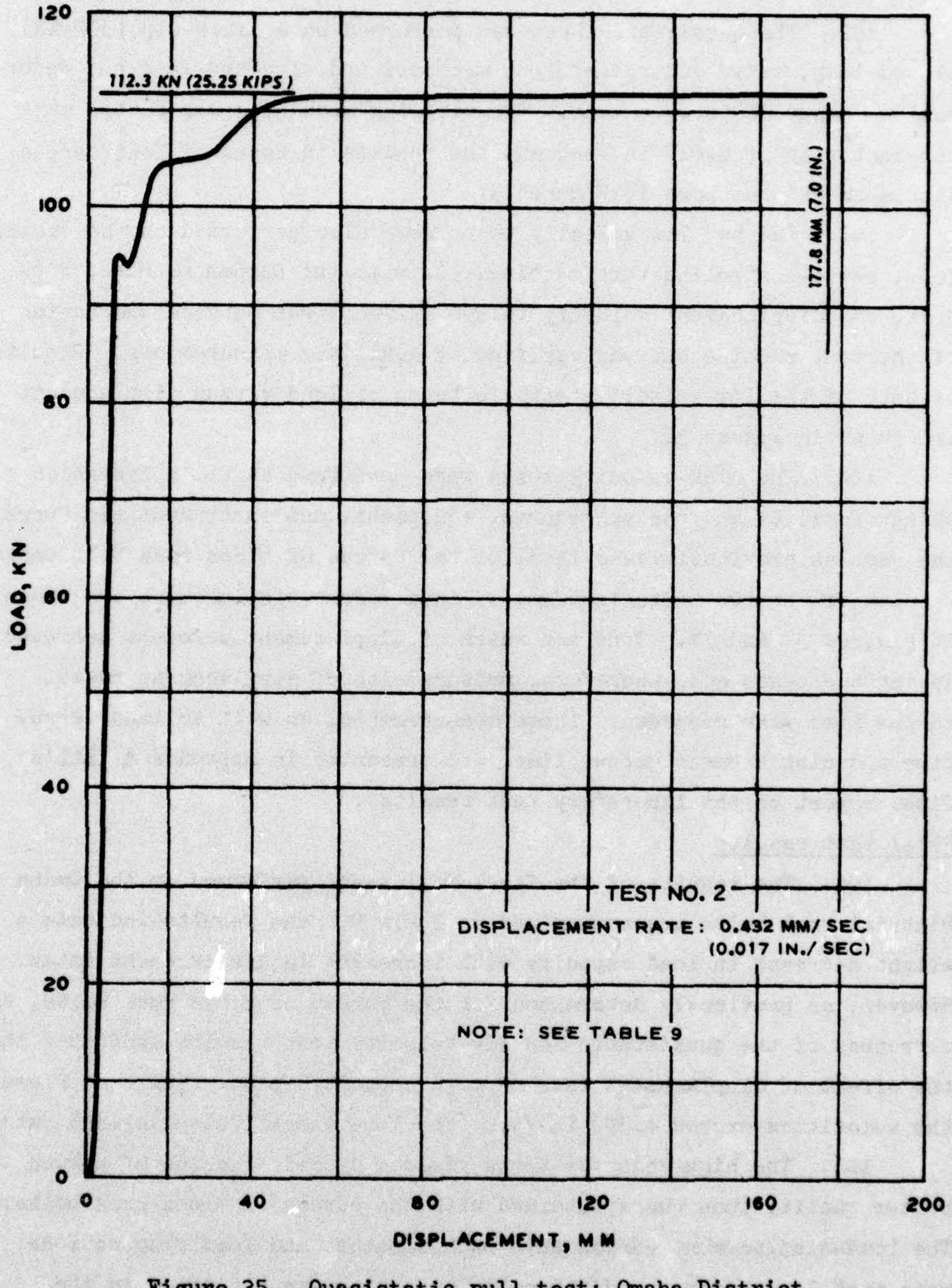


Figure 35. Quasistatic pull test; Omaha District yielding mechanism

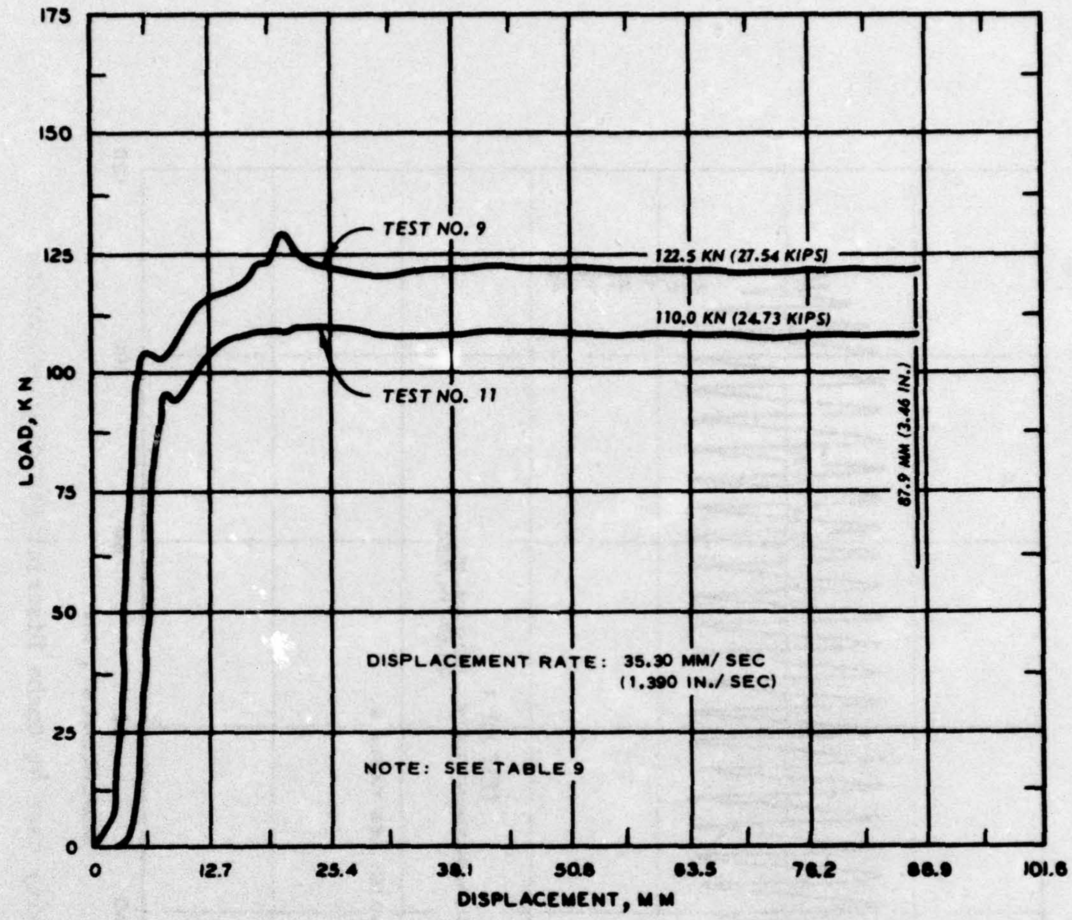


Figure 36. Low-velocity pull tests; Omaha District yielding mechanism

shank portion of the Omaha District rock bolts and was noted for the Bureau of Mines rock bolts.

Field Testing

107. At the time of this report writing, no field tests have been conducted with the Omaha District rock bolts. It is anticipated, however, that in the relatively near future field installations will be made in order to provide an additional performance appraisal.

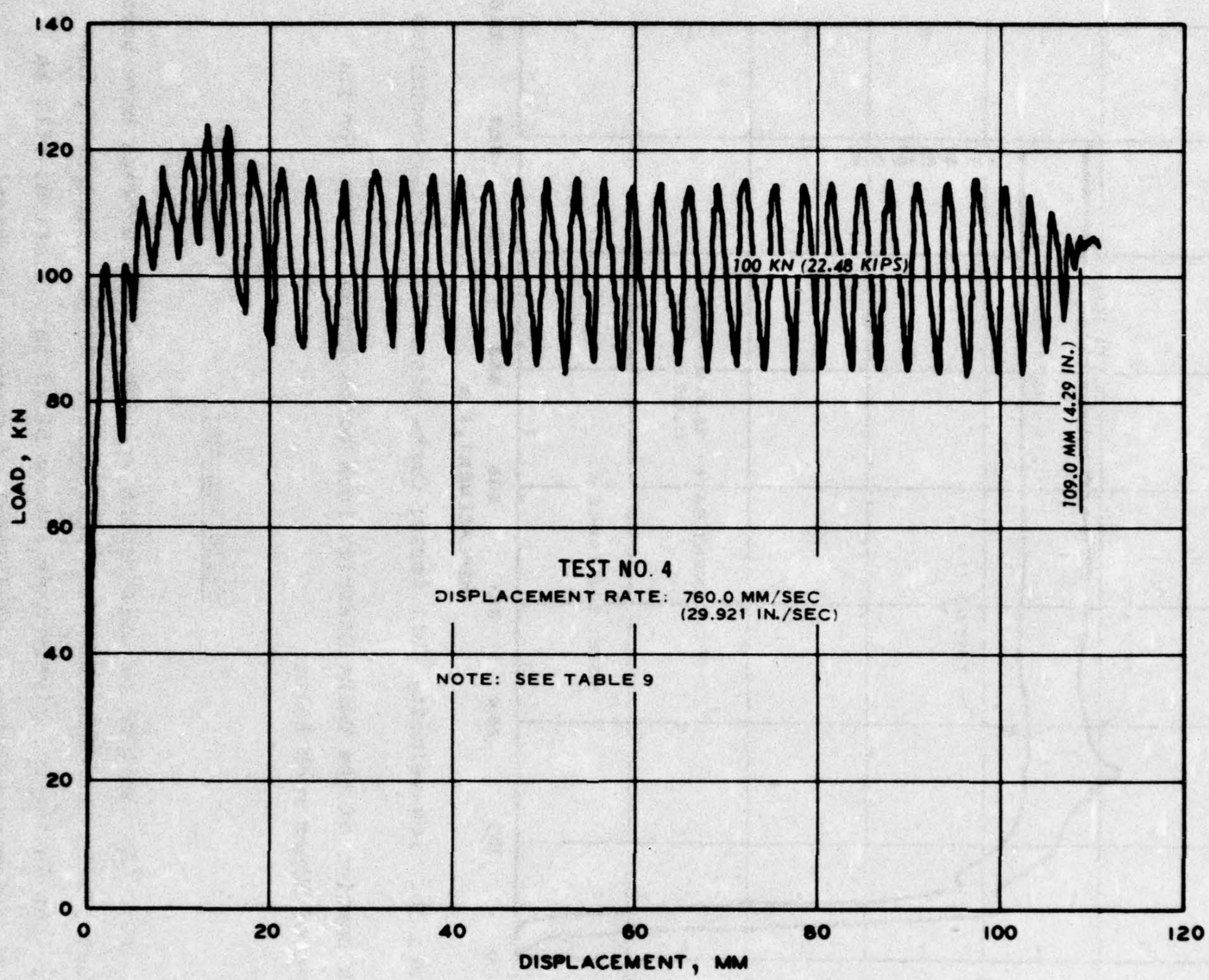


Figure 37. High-velocity test 4; Omaha District yielding mechanism

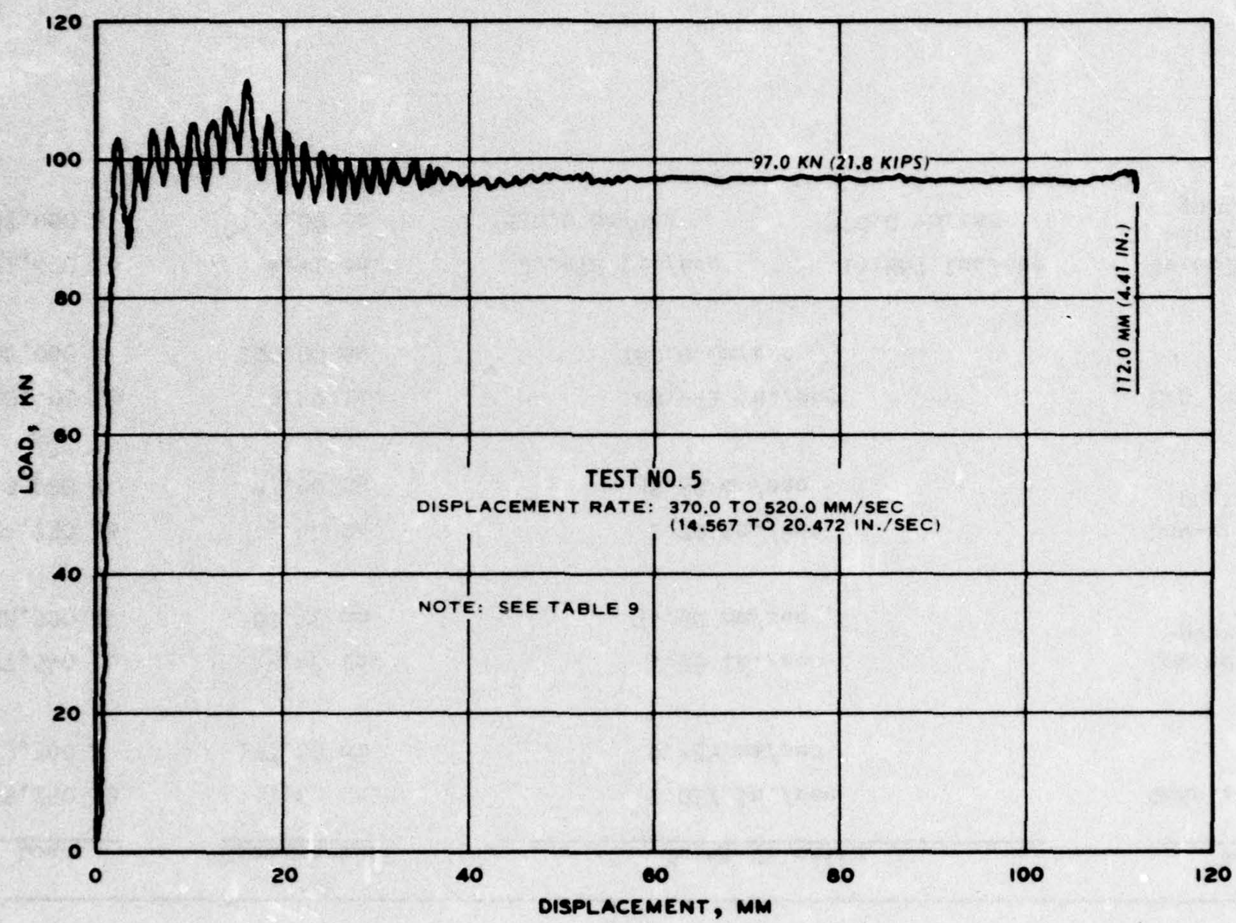


Figure 38. High-velocity test 5; Omaha District yielding mechanism

Table 9

Omaha District Yielding Mechanism Pull Test Results

Test No.	Load	Joint Displacement	Joint Velocity		Remarks
2	25,250 lb 112,300 N	7.00 in. 177.80 mm	0.017 in./sec 0.432 mm/sec		Quasistatic test
9	27,540 lb 122,500 N	3.46 in. 87.90 mm	1.39 in./sec 35.30 mm/sec		Low-velocity test; poor specimen
11	24,730 lb 110,000 N	3.46 in. 87.90 mm	1.39 in./sec 35.30 mm/sec		Low-velocity test; poor specimen
4	22,480 lb 100,000 N	4.29 in. 109.00 mm	29.921 in./sec 760.0 mm/sec		High-velocity test
5	21,800 lb 97,000 N	4.41 in. 112.00 mm	20.472 in./sec 520.0 mm/sec	14.567 in./sec 370.0 mm/sec	Velocity dropped during latter part of loading

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

108. The two basic types of yieldable rock bolts which were evaluated during this study, i.e., the "die-thread" and the "plug-tubing" types, appear to offer an excellent means of accommodating large displacements while maintaining relatively constant resistances. The testing program, however, revealed certain advantages and disadvantages of each design as follows.

Construction

109. With both types of yielding mechanisms the physical shape or configuration of the component parts was shown to be of critical importance. The South African and Bureau of Mines yielding mechanisms offer resistance to movement by the progressive flattening of rolled threads on the rock bolt and by friction developed between the flattened threads and the die. The developed resistance to movement is primarily a function of the shape of the die rather than technique of construction. In South Africa both machined dies and hot-forged dies were tested for use and it was determined that, provided the shape requirements were met, the actual dimensional tolerances are not rigorous.

110. The Omaha District yielding mechanism offers resistance to movement by controlling the amount of force required to draw a hardened tapered steel plug through a length of steel mechanical tubing. Again it was the shape of the plug that was of primary importance. While factors such as tubing thickness and tubing stiffness (resistance to bending and expansion) were important in determining the resistance developed by the yielding mechanism, it was the number of angles and physical shape of the steel plug that had the most influence on the resisting force.

111. For the two yieldable rock bolts the sensitivity of yield loads to construction methods appears to be comparable. The cost, however, is expected to be somewhat higher for the Omaha District yielding mechanism than for the others in that assembly procedures, i.e.,

insertion of the plug into the tubing, are more involved.

Performance

112. The yielding mechanisms performed in accordance with design criteria under static and quasistatic loading conditions. The primary difference noted between the Bureau of Mines and Omaha District yielding mechanisms was that there was a difference in the amount of displacement required before the yielding mechanisms reached a peak resisting force. The design of the South African and Bureau of Mines yielding mechanisms requires the rock bolt to be displaced until all of the threads have become fully engaged within the die before maximum yield loads are obtained. The design of the Omaha District yielding mechanism requires only a minute displacement to reach a peak resisting force because the expansion plugs are fully engaged in the tubing during construction. The Omaha District yieldable rock bolts thus have a quicker reaction time than either of the other two rock bolts.

113. Under dynamic loading conditions both types of yielding mechanisms which were tested exhibited rate effects. Increases in velocity of the bolts gave higher loads at which the yielding mechanisms yielded for the Bureau of Mines rock bolts. Measurements for the Omaha District yielding mechanisms, however, indicated the opposite trend, with slight decreases in yield load with increases in velocity. The velocity at which the rate effects begin was not determined; however, it was noted that the rate is probably in excess of the quasistatic velocity, 1.39 in./sec.

114. The types of resistance provided by each bolt tested were similar. Each was shown to provide about one-third of the resistance in the form of frictional resistance. The "quality" of the resistance, however, varied between the two types of yielding mechanisms tested by LLL. The Omaha District yielding mechanism gave a substantially smoother plot of yield load versus displacement. The reason for the smoother yield load curve is that the Omaha District yielding mechanism is designed to be a lubricated system and the lubrication between the expansion plug and tubing walls tends to diminish the effects of variable tube surface conditions as well as retard the plug wear and prevent

corrosion. The variations in yield force with displacement which arise with the South African and Bureau of Mines yielding mechanisms are a result of the deformation of the rolled threads and the friction obtained from variable surface conditions within the die.

115. Each yielding mechanism tested proved to be satisfactory whether tested in the laboratory, in the field, or both. The only problems noted during the testing program were losses of resisting forces which occurred when the tubing split on the Omaha District yielding mechanism, and when the threads tended to shear rather than deform plastically on the South African and Bureau of Mines yielding mechanisms. These problems, however, were basic design problems and were resolved during the early stages of the testing program.

Recommendations

116. Both types of yieldable rock bolts are recommended for use in locations of expected movement, displacement, or failure. The Omaha District yieldable rock bolts, however, offer the advantage of providing an easily lubricated system and a quicker reaction time, i.e., they require less displacement to reach the peak resisting force.

117. The yielding mechanism provided with the Omaha District yieldable rock bolt provides an excellent corrosion protection when lubricated. Rock bolts are often installed in corrosive environments which tend to reduce the life of the bolts. In the case of yieldable rock bolts, it is easily conceivable that the resisting forces could also be reduced by corrosion. The Bureau of Mines yieldable rock bolt presents a different situation from that discussed above, in that its yielding mechanism is situated on the external end of the rock bolt.

118. Due to the above-mentioned corrosive potential in rock bolt installations, an efficient means of providing and maintaining lubrication for the South African type, and possibly the Bureau of Mines type, of yielding mechanisms should be investigated. The exposed threads on the rock bolts are exceptionally vulnerable to corrosion and thus the potential for load loss exists. In the event either the South African

or the Bureau of Mines yieldable rock bolts are lubricated, the yield loads should be reevaluated. The experience gained in laboratory testing of the Omaha District yieldable rock bolts indicated decreases in yield loads of approximately one-third with lubrication; similar reactions are expected with the South African and Bureau of Mines rock bolts.

119. A future limited laboratory testing program evaluating the creep and relaxation potential of the two types of yielding mechanisms is recommended. In the testing covered by this report, only limited creep and relaxation tests were performed on the Omaha District yielding mechanism and none were performed on either the South African or the Bureau of Mines yielding mechanisms. A subjective evaluation of the two types of yielding mechanisms suggests that, due to the physical shape or geometry of the mechanisms, the Omaha District yielding mechanism would encounter less creep or relaxation problems.

120. The final recommendation for future testing is a full-scale field test, similar to that conducted in South Africa by Ortlepp. Under dynamically loaded conditions the performance of the two basic types of yieldable rock bolts should be evaluated. For comparative purposes it is recommended that encapsulated (limited yielding) rock bolts be included along with the yieldable rock bolts in such a testing program. The encapsulated rock bolts would serve as a standard upon which an evaluation of yieldable rock bolt performance could be based. Under controlled conditions, with adequate instrumentation, a field test of this type would provide data to the extent that a final appraisal could be made.

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APPENDIX A: SHOCK LOAD TESTING OF YIELDABLE ROCK BOLTS

MTE 75-66
May 28, 1975

ENS 75-16

FINAL REPORT

SHOCK LOAD TESTING OF YIELDABLE ROCK BOLTS

Performed Under Interagency Agreement

No. AT(04-3)-1067

Between

U.S. Army Corps of Engineers

and

U.S. Energy Research and Development Administration

Reported By:

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INTRODUCTION

The purpose of this program was to perform force-displacement measurements on two types of rock bolts at three different rates.

The Type I bolt is designed to yield by extrusion of a hollow smooth die over rolled threads. The Type II bolt is designed to yield by extrusion of a solid smooth plug through a seamless tube.

Initially, the rates requested were quasistatic, 10 to 15 in/sec (250 to 375 mm/s) and 100 to 150 in/sec (2 500 to 3 750 mm/s). Maximum displacements requested were 2.5 in (63.5 mm) to 3.5 in (88.9 mm). It was realized early in negotiations that the high displacement rates could not be reached. A new goal of 70 in/sec (1 778 mm/s) was set. Achieving this displacement rate still proved to be beyond the capability of existing test equipment as reported herein.

Requirements to report test results in terms of graphs of force vs. displacement, force vs. time, and displacement vs. time were substantially satisfied. In addition, curves for displacement rate (joint velocity) vs. time for the dynamic tests are furnished as part of the report. Constant displacement rate could not be achieved for the dynamic tests; therefore, this information is of interest.

EQUIPMENT AND INSTRUMENTATION

The tests at deformation rates of 0.432 and 35.4 mm/s and reported here as Figures 1, 2, and 3 were performed on a 500 kN closed loop, servocontrolled test machine using standard load and deformation measuring techniques.

The remaining tests were performed at LLL's hydraulic shaker facility. Photograph 1 shows a Type I rock bolt in position for testing. The hydraulic actuator shown in the lower left of the photograph was under digital computer control. The Mod Comp III computer also served as a data acquisition and data reduction device.

Instrumentation was more extensive on these dynamic tests:

A. Load was sensed from an in-line load cell.

B. Acceleration was sensed from an accelerometer mounted on the actuator load foot.

C. Ram displacement was sensed by transducer built into the actuator mechanism.

D. Joint displacement was sensed by a direct measurement between the rock bolt shank and its deforming body. The sensing element was a dynamic rated slide potentiometer.

RESULTS AND DISCUSSION

Figure 1 shows the results of tests on one Type I and one Type II bolt at 0.432 mm/s deformation rate. Since these tests were performed on a closed loop, servocontrolled test machine, the load-time curve can be inferred from the figure by rescaling the horizontal axis. The deflection-time curve is a linear ramp.

Similar remarks apply to Figures 2 and 3. Although the displacement velocity is outside the rating of the closed loop, servocontrolled test machine, we confirmed by auxiliary measurements that the deflection-time ramp did not deviate from linearity by more than 5%. There were anomalies in each of the Type II specimens used in these tests. The Type II specimens whose results are shown in Figure 2 apparently had an outsized cone, which yielded a portion of the seamless tube when it was forced into starting position. The Type II specimen whose results are shown in Figure 3 apparently had an undersized cone. It was slipped past the end of the seamless tube by approximately 12 mm in its as-received condition. These anomalies in manufacture could contribute to the differencies in results for these two tests.

The remaining discussion refers to the high rate tests. All were performed with the equipment depicted in Photograph 1.

Figures 4, 5, 6, and 7 are load vs. time, joint displacement vs. time, joint velocity vs. time, and load vs. joint displacement for a Type I bolt. As can be seen from the curves, pertinent values are open to some interpretation. We read the load as 123 kN, the displacement as 67.5 mm and the velocity at the beginning of the test as 550 mm/s and at the latter part of the test as 300 mm/s.

Figures 8, 9, 10, and 11 are load vs. time, joint displacement vs. time, joint velocity vs. time, and load vs. joint displacement for a Type I bolt. We read the load as 120 kN, the displacement as 47 mm, the initial joint velocity as 962 mm/s and the final joint velocity as 240 mm/s. This was the last dynamic test performed, since the fixturing at the end opposite the actuator failed. This failure was the reason for the low joint displacement.

Figures 12, 13, 14, and 15 are load vs. time, joint displacement vs. time, joint velocity vs. time,and load vs. joint displacement for a Type I bolt.

We read the load as 124 kN, the joint displacement as 39.5 mm, initial joint velocity as 1 065 mm/s and the final joint velocity as 180 mm/s.

All of the Type I bolts yielded in the shank position by about 50 mm during the dynamic tests. This yielding, plus the unsteady deformation characteristic of the threaded portion contributed to the widely varying velocity-time response.

Captions on Figures 4 through 15 use "Threaded Bolt" to describe the Type I bolt.

Figures 16, 17, 18, and 19 are load vs. time, joint displacement vs. time, joint velocity vs. time, and load vs. joint displacement for a Type II rock bolt. We read the load as 97 kN, the displacement as 113 mm. Initial velocity was 520 mm/s and it settled to 370 mm/s in the latter portion of the loading time.

Figures 20, 21, 22, and 23 are load vs. time, joint displacement vs. time, joint veloicty vs. time, and load vs. joint displacement for a Type II rock bolt. We read the load as 100 kN, the displacement as 109 mm and the steady joint velocity as 760 mm/s.

Captions on Figures 16 through 23 use "Ext Bolt" to describe the Type II bolt.

It was possible to generate much better dynamic records for the Type II bolts than for the Type I. Since the tests were intermixed, the unsteady deformation of the Type I bolt is probably real. The severity could have been enhanced in the records by the fact that the long extender rod which coupled the bolt to the anchor contributed a significant amount of compliance to the test string. The test results could possibly have been improved by replacing the extender bolt with a much more rigid structure. See Photograph 1. In addition, yielding was not noted in the shank portion of the Type II bolts as it was for the Type I bolts.

There seems to be an increase in load capacity as a function of rate for the Type I bolts, and a slight decrease for the Type II bolts. The tests at 35.4 mm/s were performed last, in an effort to support this difference by measurement. No change was found between these tests and the tests performed at 0.432 mm/s. If there is a rate effect, the mechanism responsible for it must operate at joint velocities above 35.4 mm/s.

The energy storage characteristic of the Type II bolts seems better at all rates than the Type I bolts. Since this is a significant parameter in rock bolt service, it should be noted as an advantage of the Type II design.

Table I summarizes results for the Type I bolts as reported herein. Table II is a summary of results for the Type II bolts.

IMPROVEMENTS FOR FUTURE TESTING

These tests represent a best effort by LLL within the time and budgetary constraints imposed. However, there are possibilities for improving test performance at a rather modest cost, if future testing is desired.

The most attractive way is to gang four actuators together to drive a displacement doubling mechanism, to improve the dynamic setup depicted in Photograph 1. These modifications could be done for an estimated $15,000.

A second method that was studied was a drop weight test. Two features need to be noted. First, a very large dropping mass would have to be built. Second, a shock pad would have to be designed that would permit a rapidly rising load, but suppress wave propagation effects. Several specimens would have to be sacrificed to "tune" this system. The first method mentioned above seems more attractive and no more expensive to realize.

DISPOSITION OF SPECIMENS

Specimens will be returned to Waterways Experiment Station,C.O.D.

ACKNOWLEDGEMENTS

Others who contributed significantly to this program were Ed Dean, Frank Dodd, Dennis Fisher, Al Taylor, Bob Scott, Bob Winkler, and members of the hydraulic shaker crew.

CAT:MDM

TABLE I

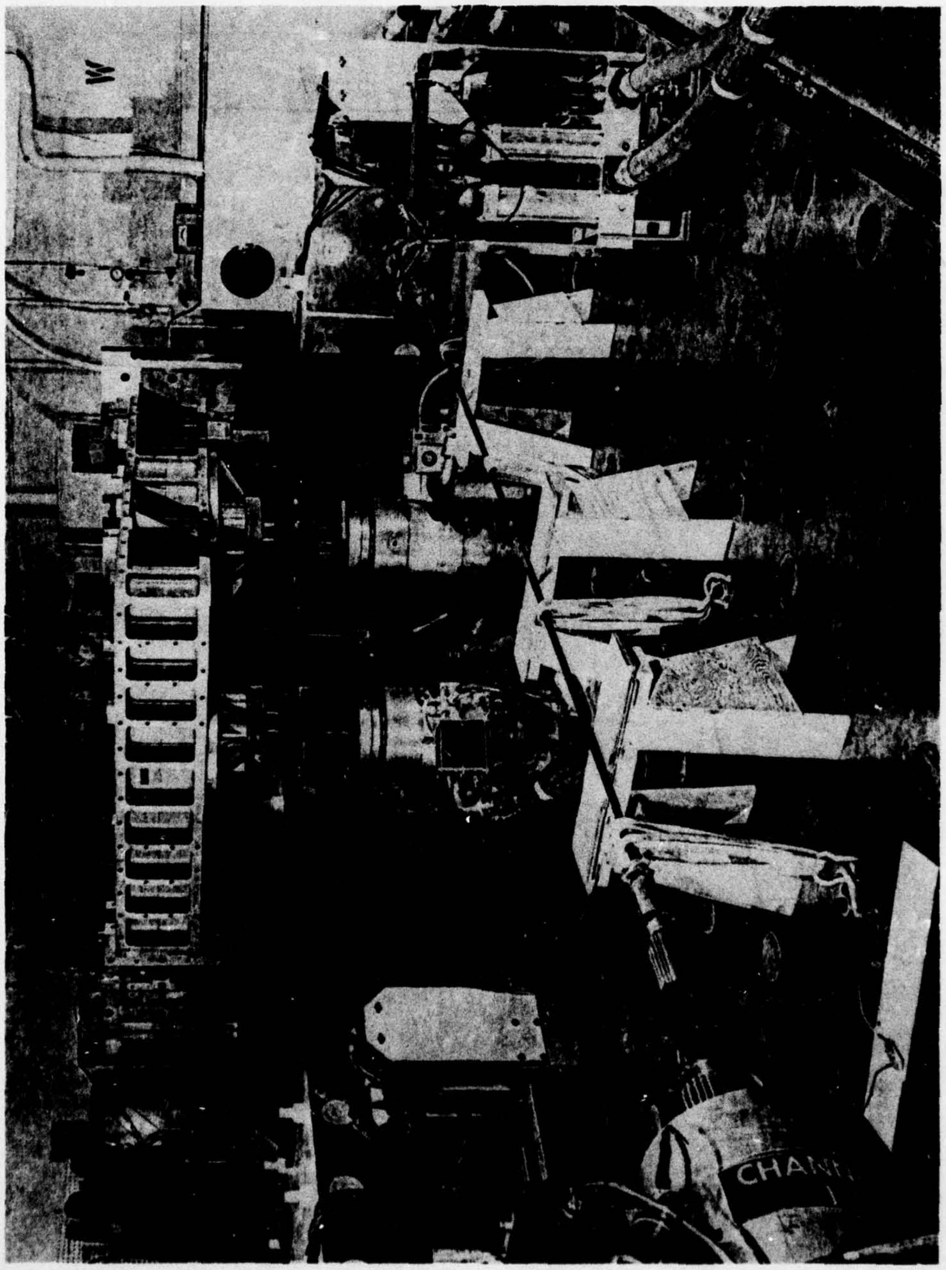
TYPE I ROCK BOLT TEST RESULTS

Test No.	Load	Joint Displacement	Joint Velocity		Remarks
1	19,000 lb. 84 500 N	6.70 in. 170.00 mm	0.017 in/sec. 0.432 mm/s		
8	19,390 lb. 86 250 N	3.30 in. 83.82 mm	1.390 in/sec. 35.300 mm/s		
10	20,230 lb. 90 000 N	3.30 in. 83.82 mm	1.390 in/sec. 35.300 mm/s		
6	27,650 lb. 123 000 N	2.66 in. 67.50 mm	21.6 in/sec. 550.0 mm/s	11.8 in/sec. 300.0 mm/s	Velocity dropped during latter part of loading
7	26,970 lb. 120 000 N	1.85 in. 47.00 mm	37.8 in/sec. 962.0 mm/s	9.4 in/sec. 240.0 mm/s	Last dynamic test. Fixturing failed.
3	27,870 lb. 124 000 N	1.56 in. 39.50 mm	41.9 in/sec. 1 065.0 mm/s	7.1 in/sec. 180.0 mm/s	Shank yielded under dynamic load in all cases.

TABLE II

TYPE II ROCK BOLT TEST RESULTS

Test No.	Load	Joint Displacement	Joint Velocity	Remarks
2	25,250 lb. 112 300 N	7.00 in. 177.80 mm	0.017 in/sec. 0.432 mm/s	
9	27,540 lb. 122 500 N	3.46 in. 87.90 mm	1.39 in/sec. 35.30 mm/s	Poor specimen.
11	24,730 lb. 110 000 N	3.46 in. 87.90 mm	1.39 in/sec. 35.30 mm/s	Poor specimen.
5	21,800 lb. 97 000 N	4.41 in. 112.00 mm	20.5 in/sec. 14.6 in/sec. 520.0 mm/s 370.0 mm/s	Velocity dropped during latter part of loading.
4	22,480 lb. 100 000 N	4.29 in. 109.00 mm	29.9 in/sec. 760.0 mm/s	



PHOTOGRAPH No. 1

QUASISTATIC TESTS (0.432 mm/s)

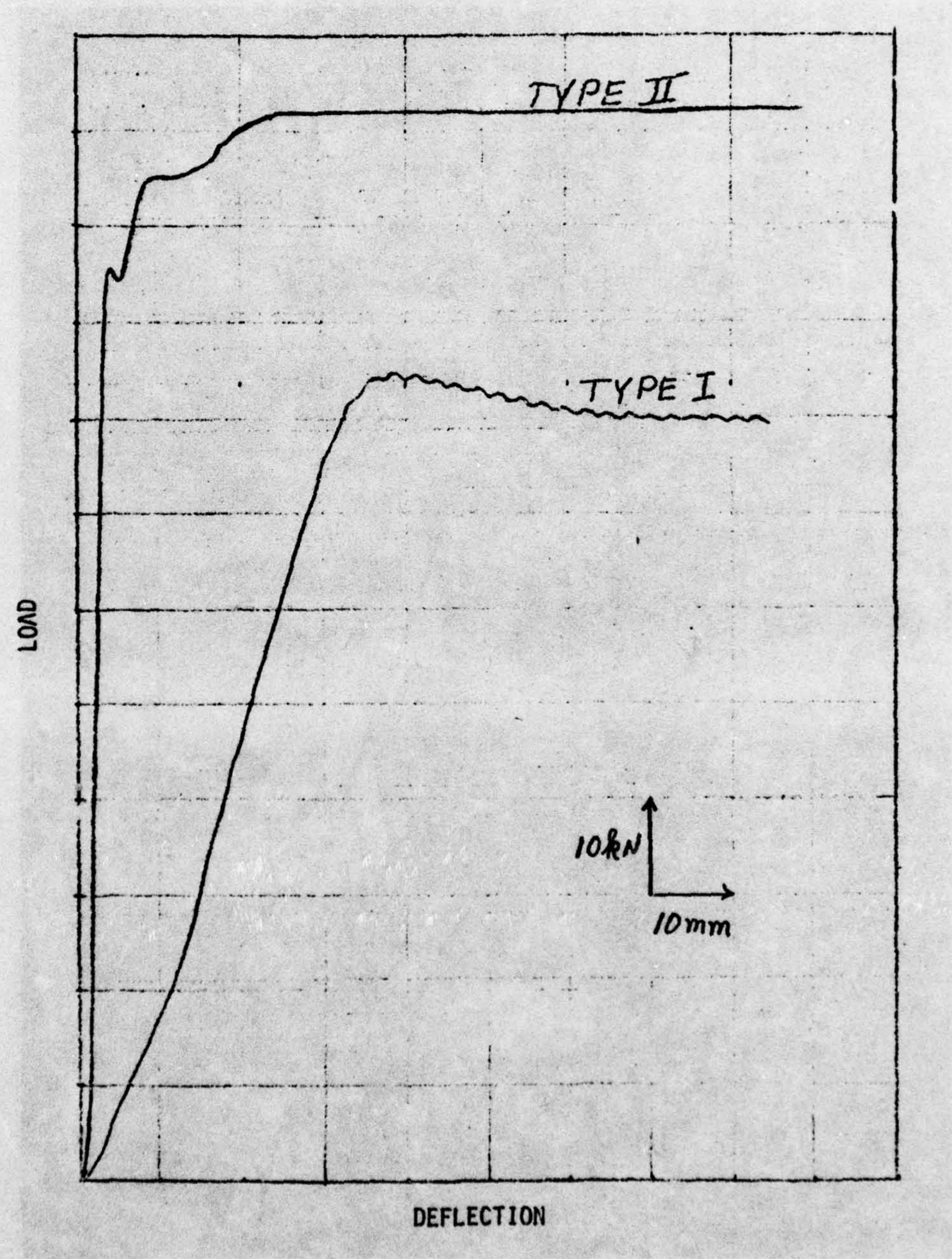


FIGURE 1

LOW VELOCITY TESTS (35.4 mm/s)

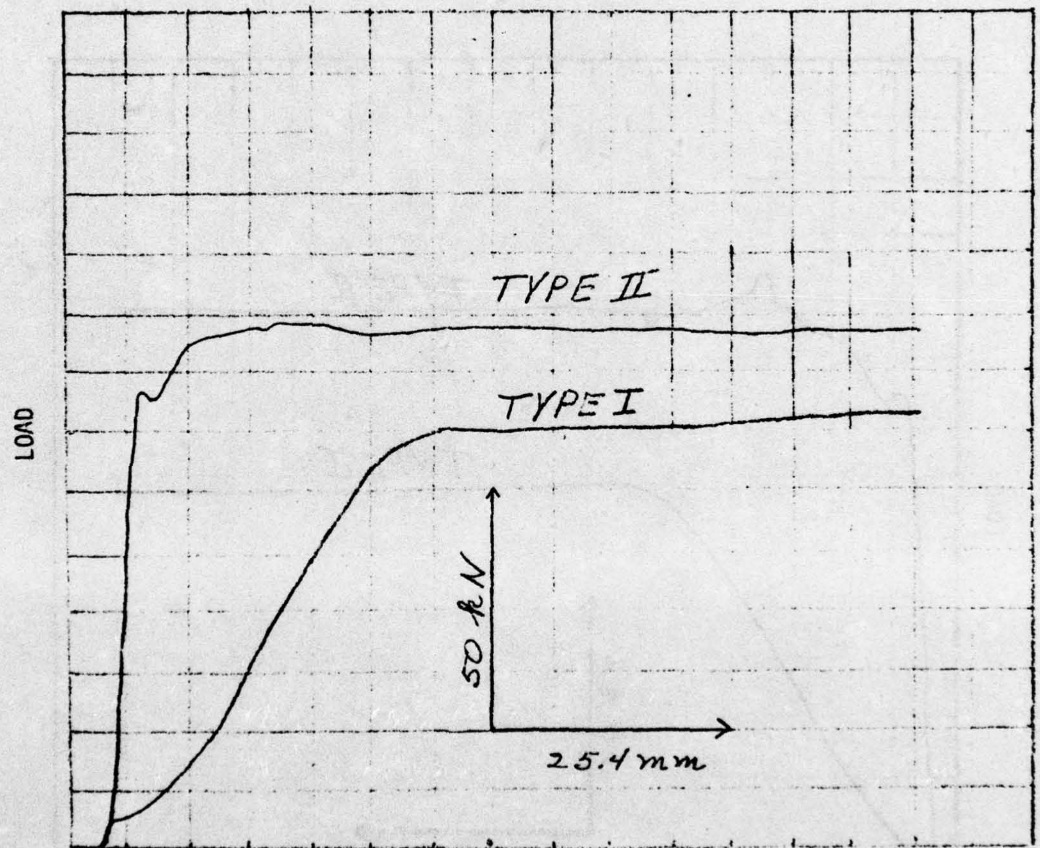


FIGURE 2

LOW VELOCITY TESTS (35.4 mm/s)

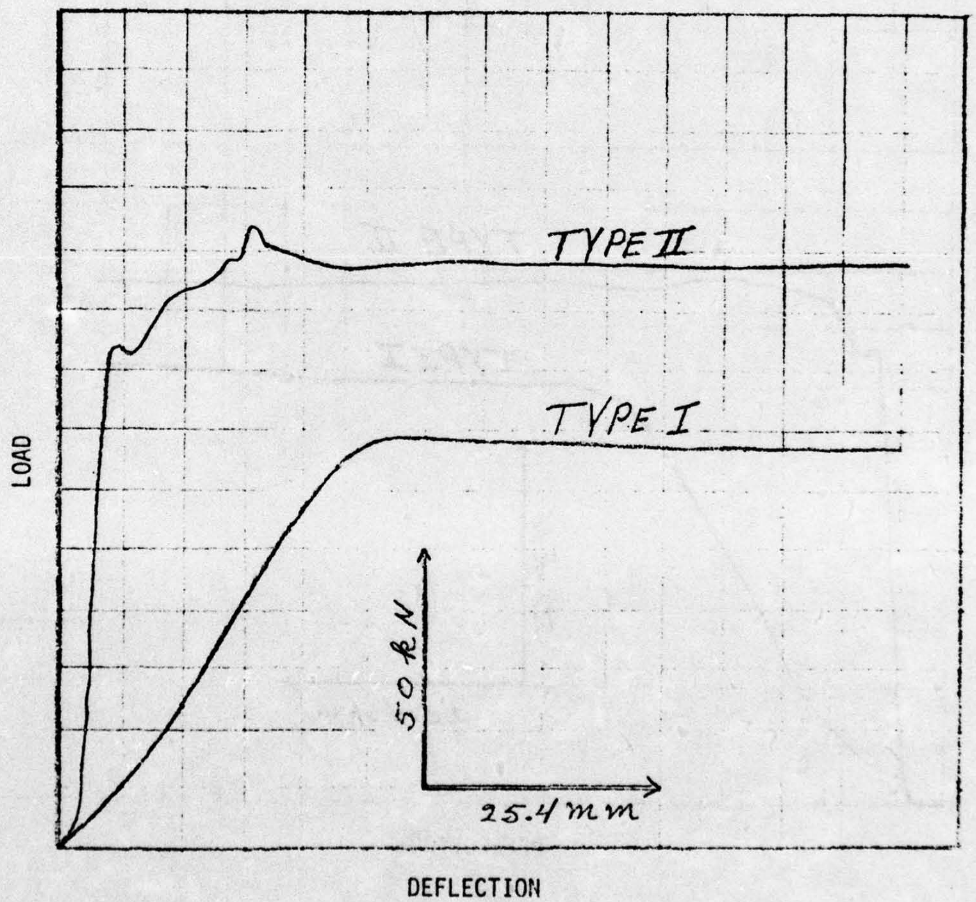


FIGURE 3

AD-A034 026 ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MISS F/G 13/5
AN EVALUATION OF THE DESIGN AND APPLICATIONS OF YIELDABLE ROCK --ETC(U)
NOV 76 W O MILLER
UNCLASSIFIED WES-TR-S-76-14 NL

2 OF 2
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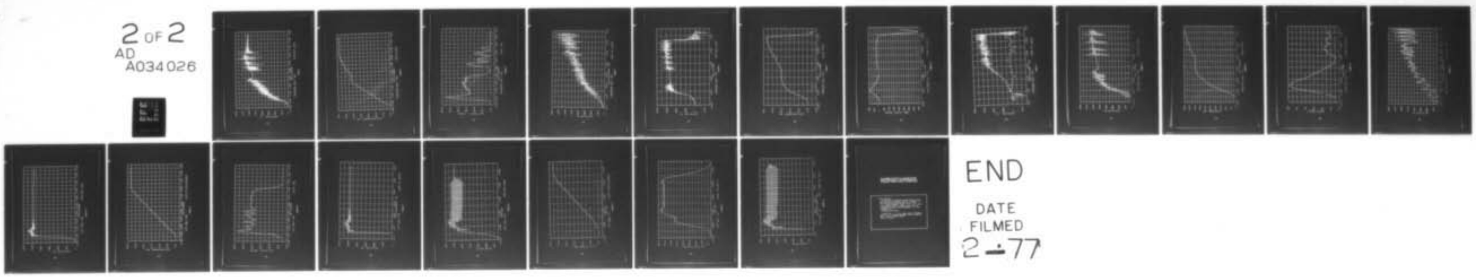
A034026



END
DATE
FILMED
2-77

1.0 2.8 2.5 3.2 2.2 3.6 4.0 2.0 1.1 1.8 1.25 1.4 1.6

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

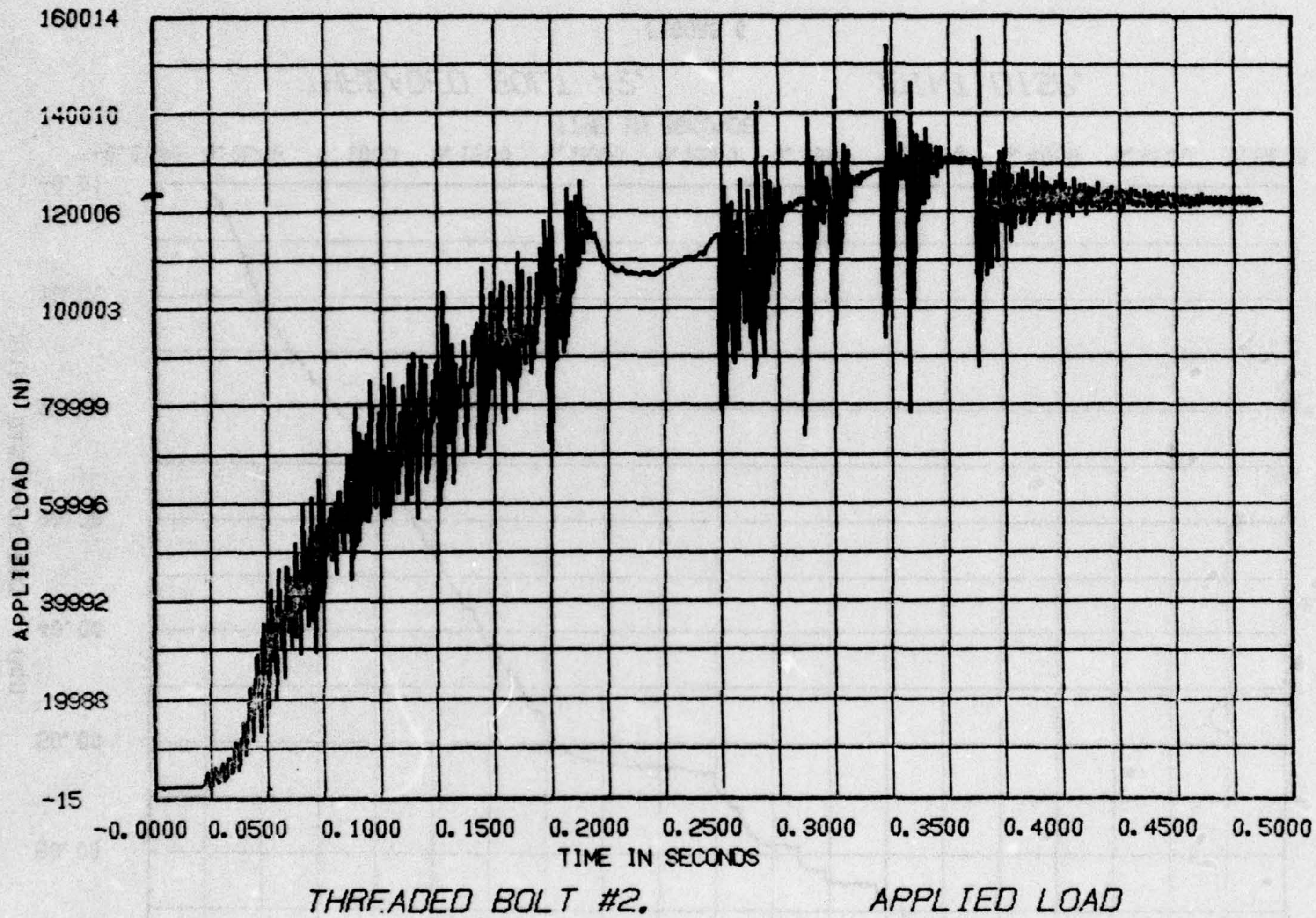
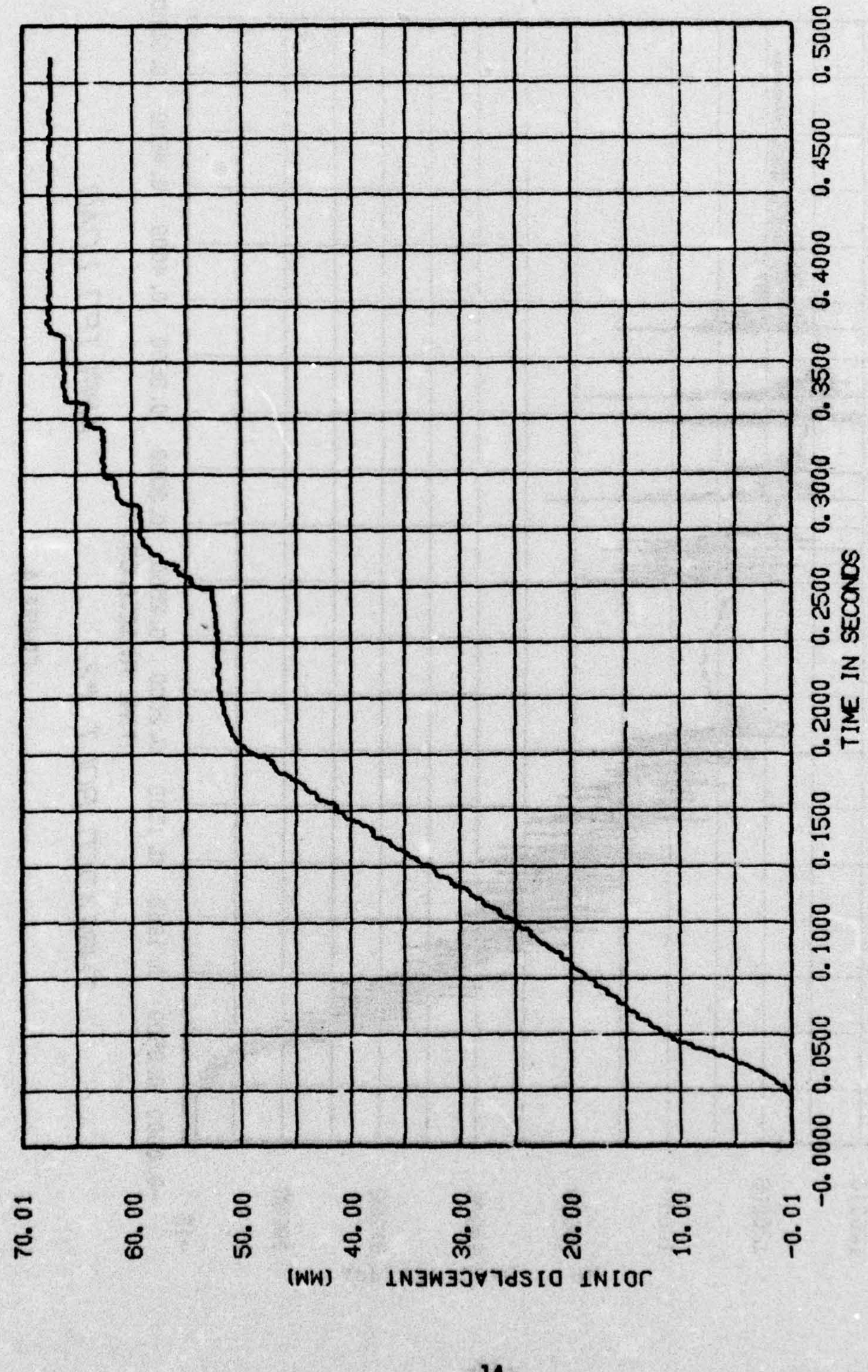

160014
140010
120006
100003
79999
59996
39992
19988
-15
APPLIED LOAD (N)
-0.0000
0.0500
0.1000
0.1500
0.2000
0.2500
0.3000
0.3500
0.4000
0.4500
0.5000
TIME IN SECONDS
THRFADED BOLT #2.
APPLIED LOAD

FIGURE 4



THREADED BOLT #2. JOINT DISP.

FIGURE 5

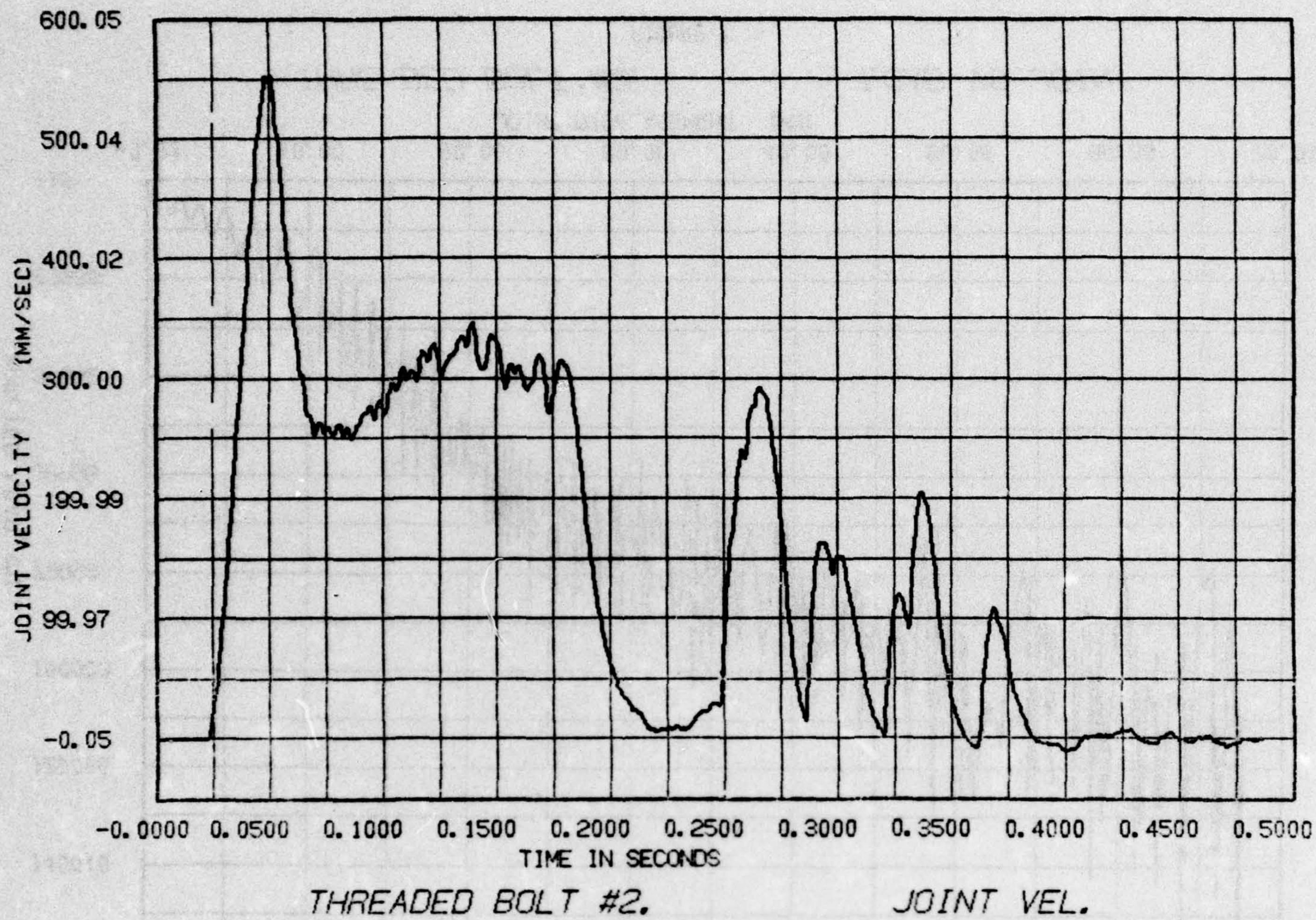
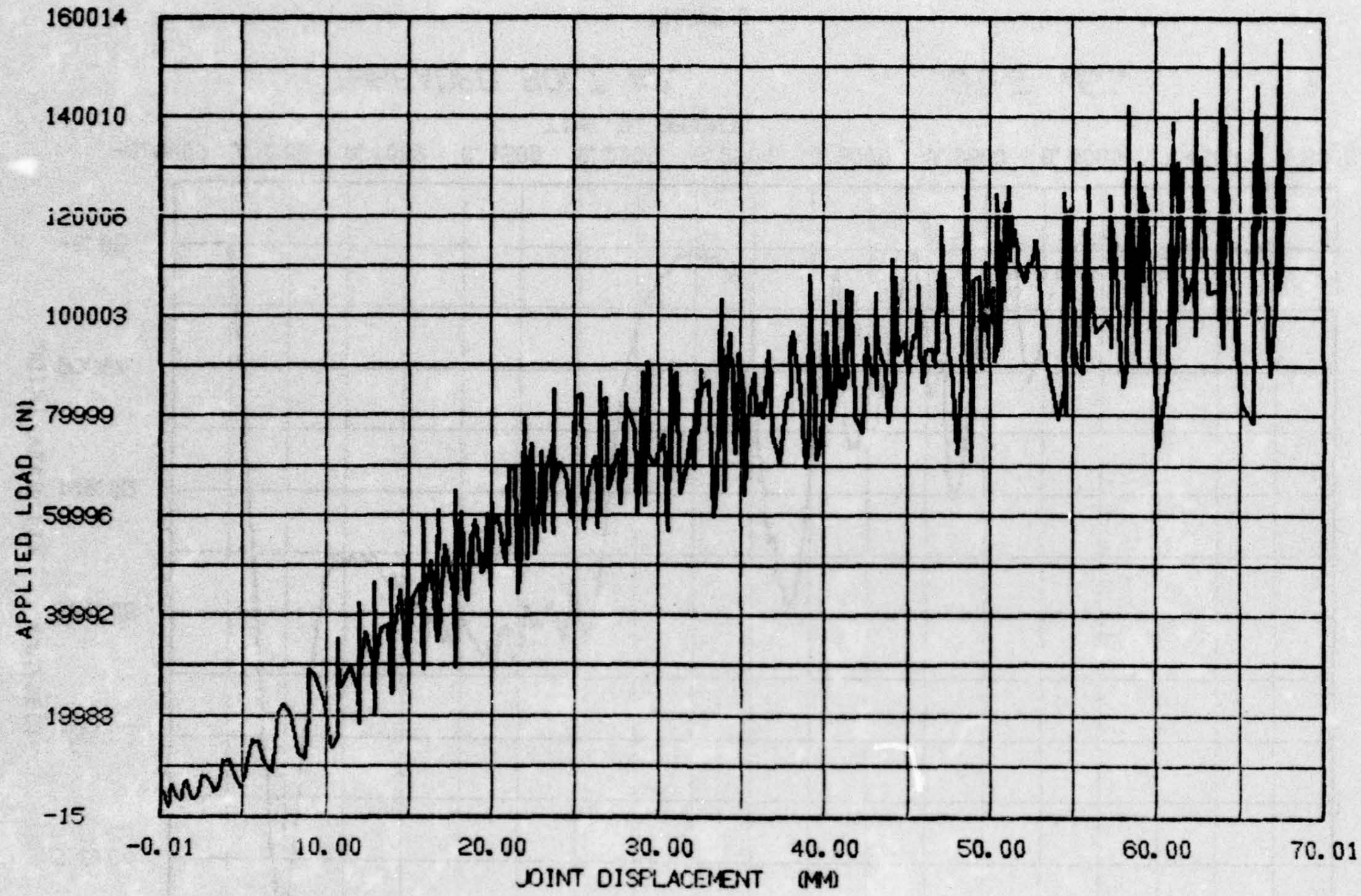
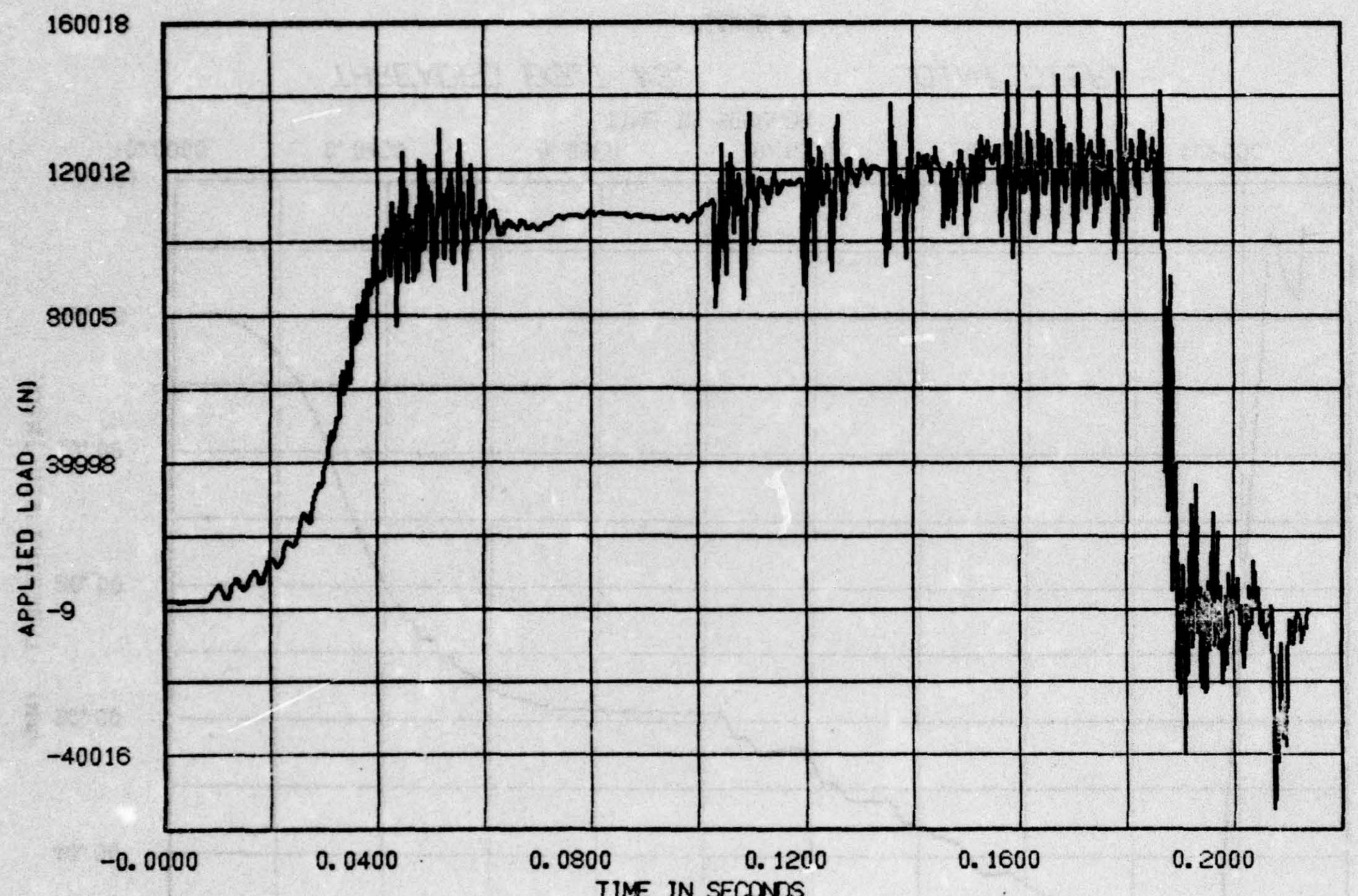

600.05
500.04
400.02
300.00
199.99
99.97
-0.05
JOINT VELOCITY (MM/SEC)
-0.0000 0.0500 0.1000 0.1500 0.2000 0.2500 0.3000 0.3500 0.4000 0.4500 0.5000
TIME IN SECONDS
THREADED BOLT #2.
JOINT VEL.

FIGURE 6



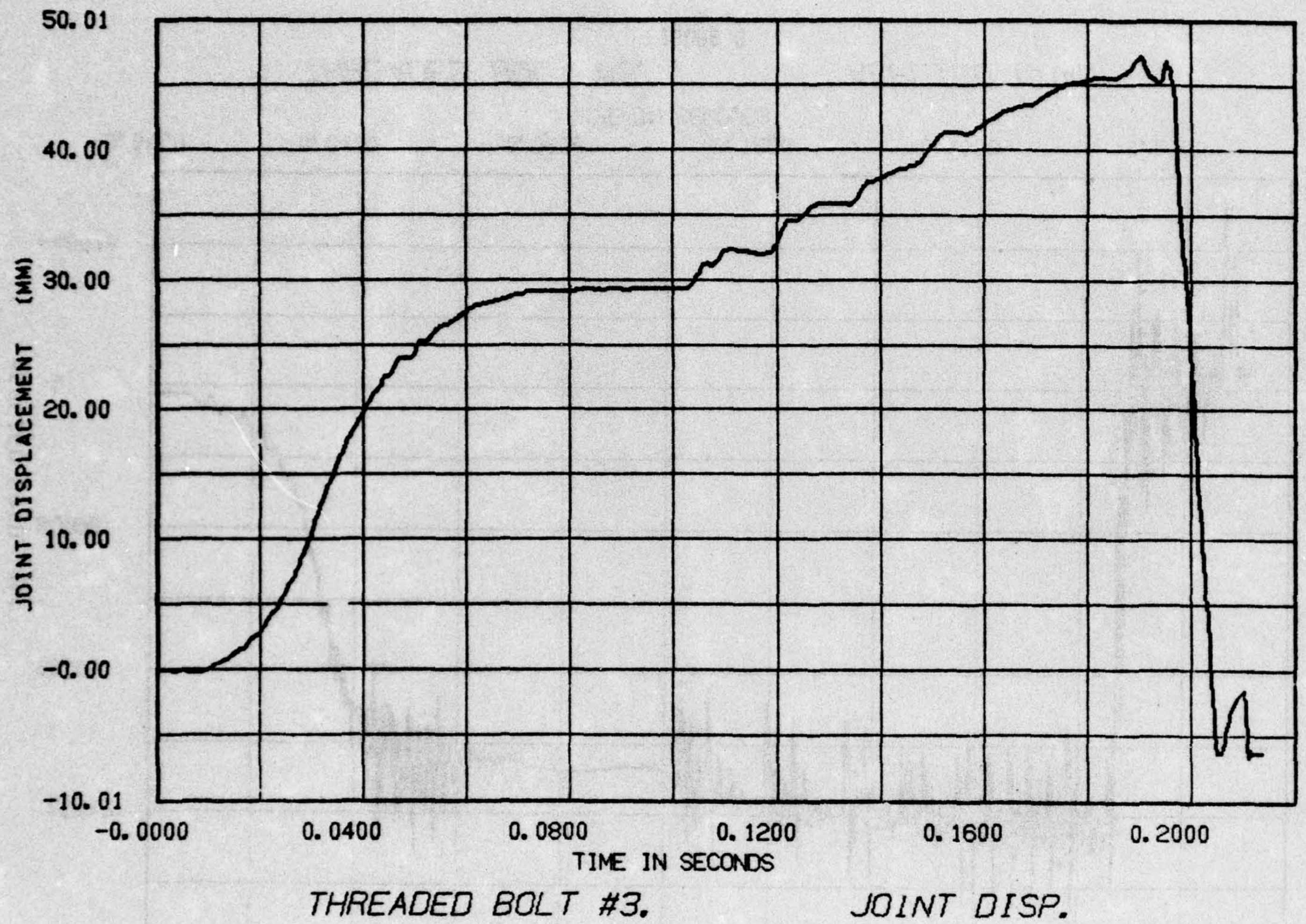
THREADED BOLT #2. LOAD VS JOINT

FIGURE 7



THREADED BOLT #3. *APPLIED LOAD*

FIGURE 8



50.01
40.00
30.00
20.00
10.00
-0.00
-10.01
JOINT DISPLACEMENT (MM)
-0.0000
0.0400
0.0800
0.1200
0.1600
0.2000
TIME IN SECONDS
THREADED BOLT #3.
JOINT DISP.

FIGURE 9

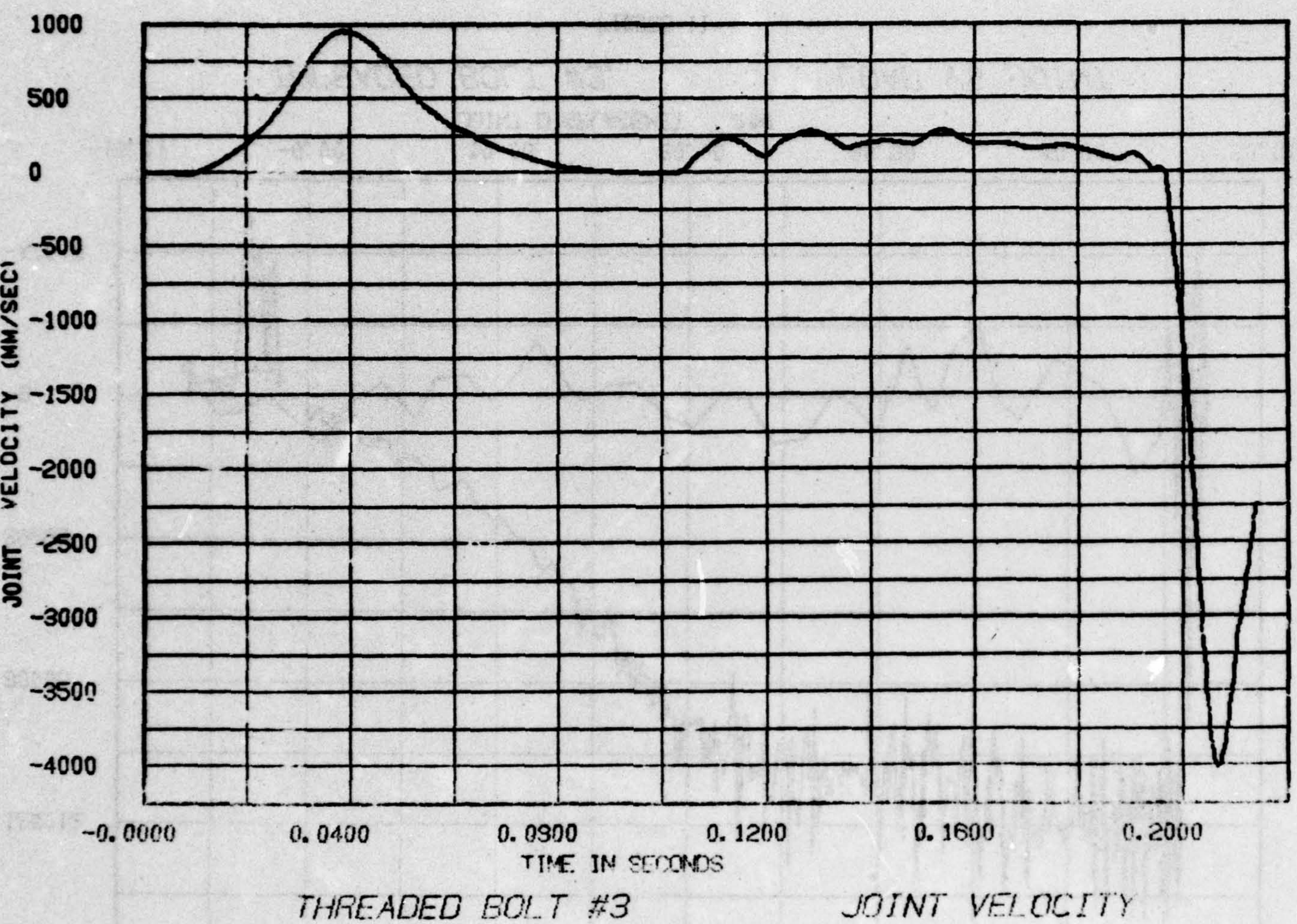

1000
500
0
-500
-1000
-1500
-2000
-2500
-3000
-3500
-4000
JOINT VELOCITY (MM/SEC)
-0.0000
0.0400
0.0800
0.1200
0.1600
0.2000
TIME IN SECONDS
THREADED BOLT #3
JOINT VELOCITY

FIGURE 10

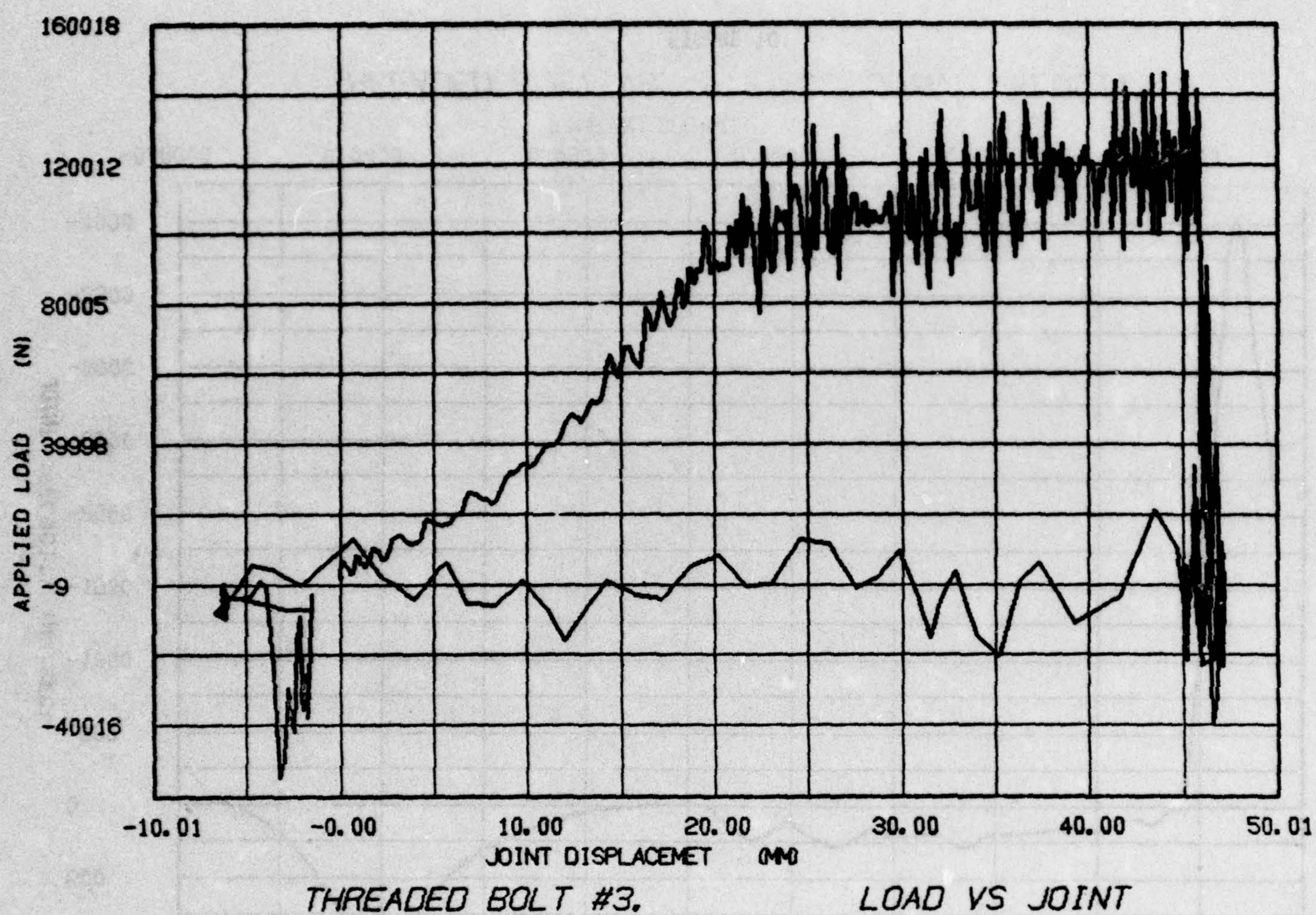

160018
120012
80005
39998
-9
-40016
APPLIED LOAD (N)
-10.01
-0.00
10.00
20.00
30.00
40.00
50.01
JOINT DISPLACEMET (MM)
THREADED BOLT #3. LOAD VS JOINT

FIGURE 11

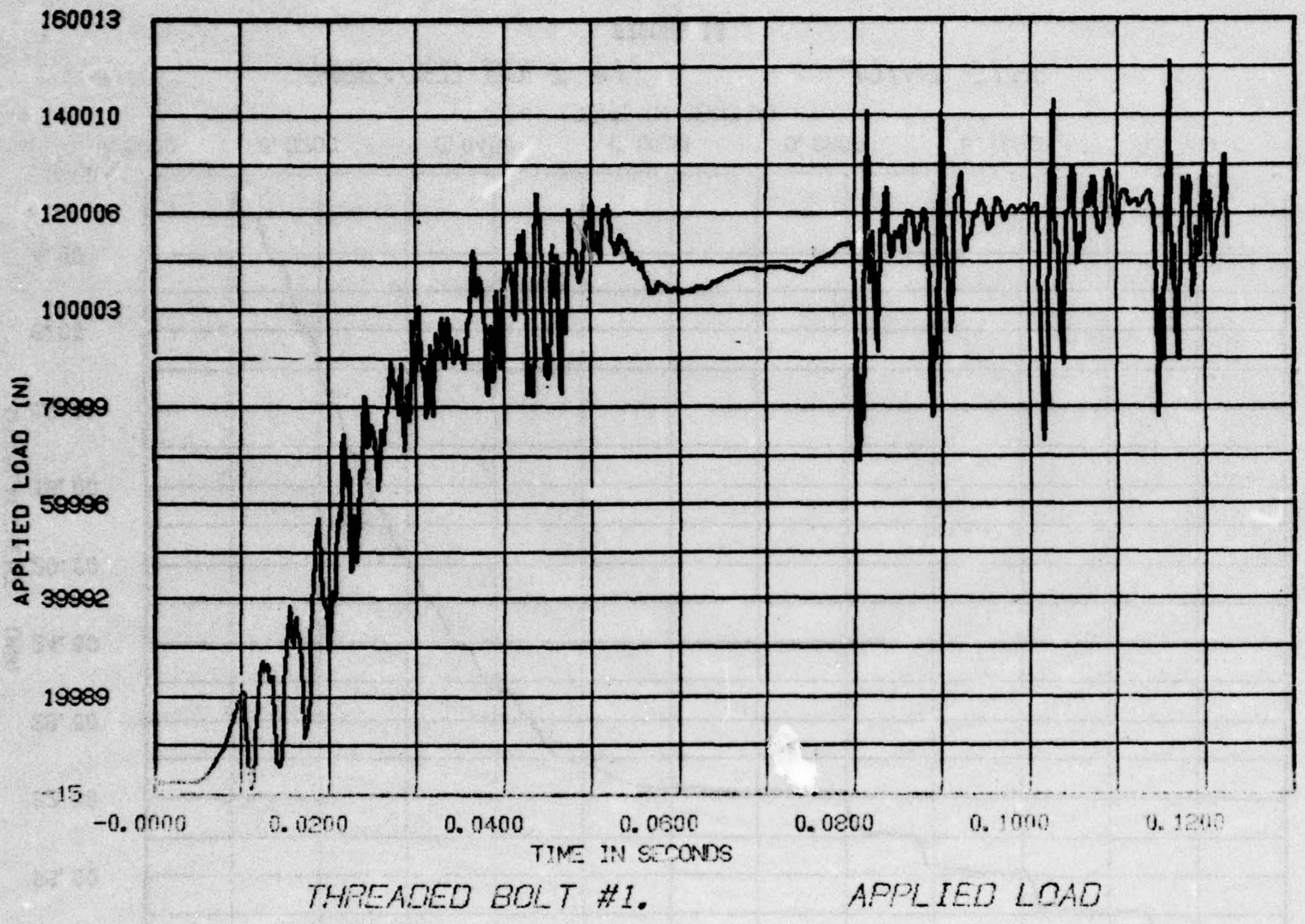
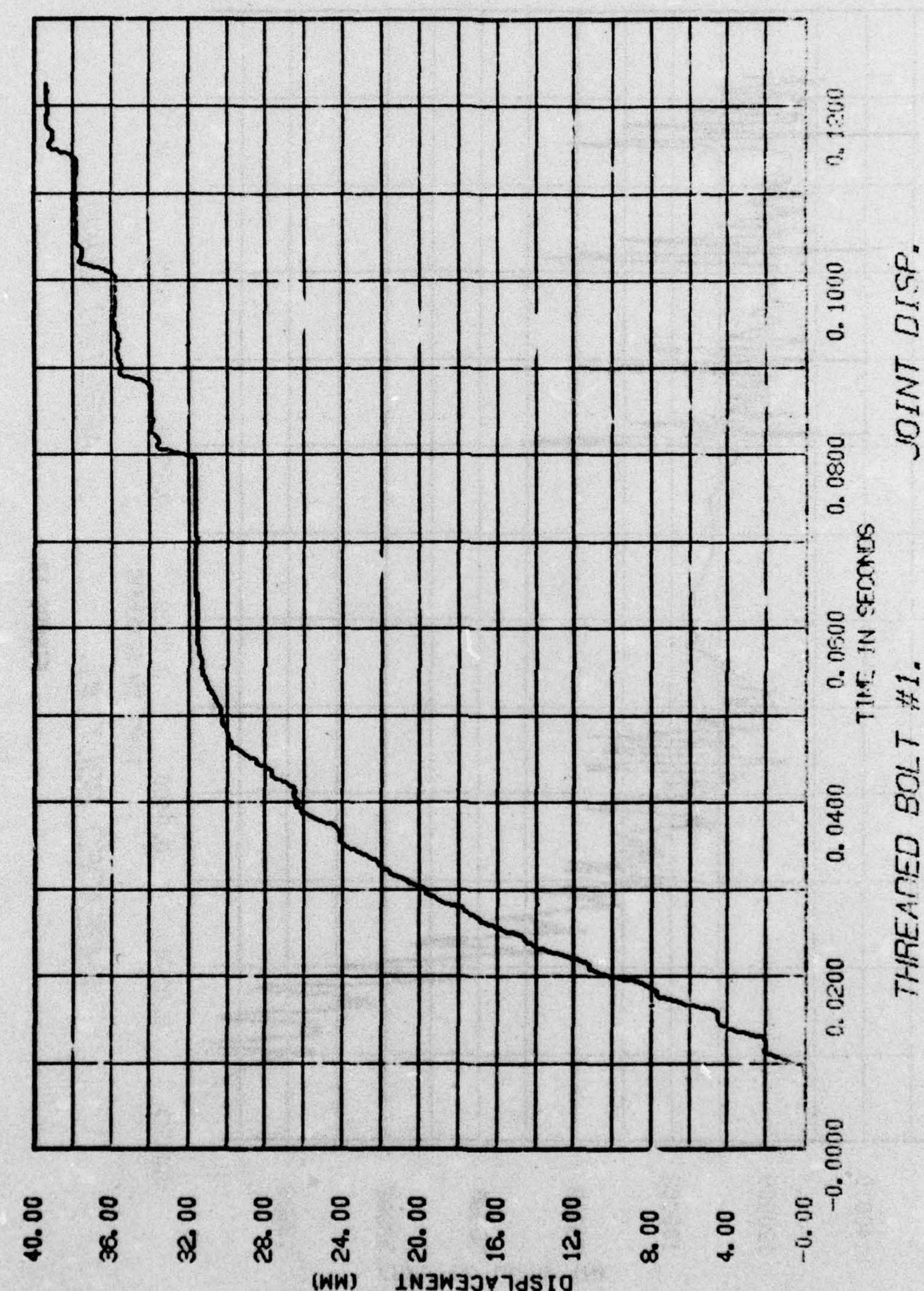

160013
140010
120006
100003
79999
59996
39992
19989
-15
APPLIED LOAD (N)
-0.0000
0.0200
0.0400
0.0600
0.0800
0.1000
0.1200
TIME IN SECONDS
THREADED BOLT #1.
APPLIED LOAD

FIGURE 12



DISPLACEMENT (MM)
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
-0.00
-0.0000
0.0200
0.0400
0.0600
0.0800
0.1000
0.1200
TIME IN SECONDS
THREADED BOLT #1. JOINT DISP.

FIGURE 13

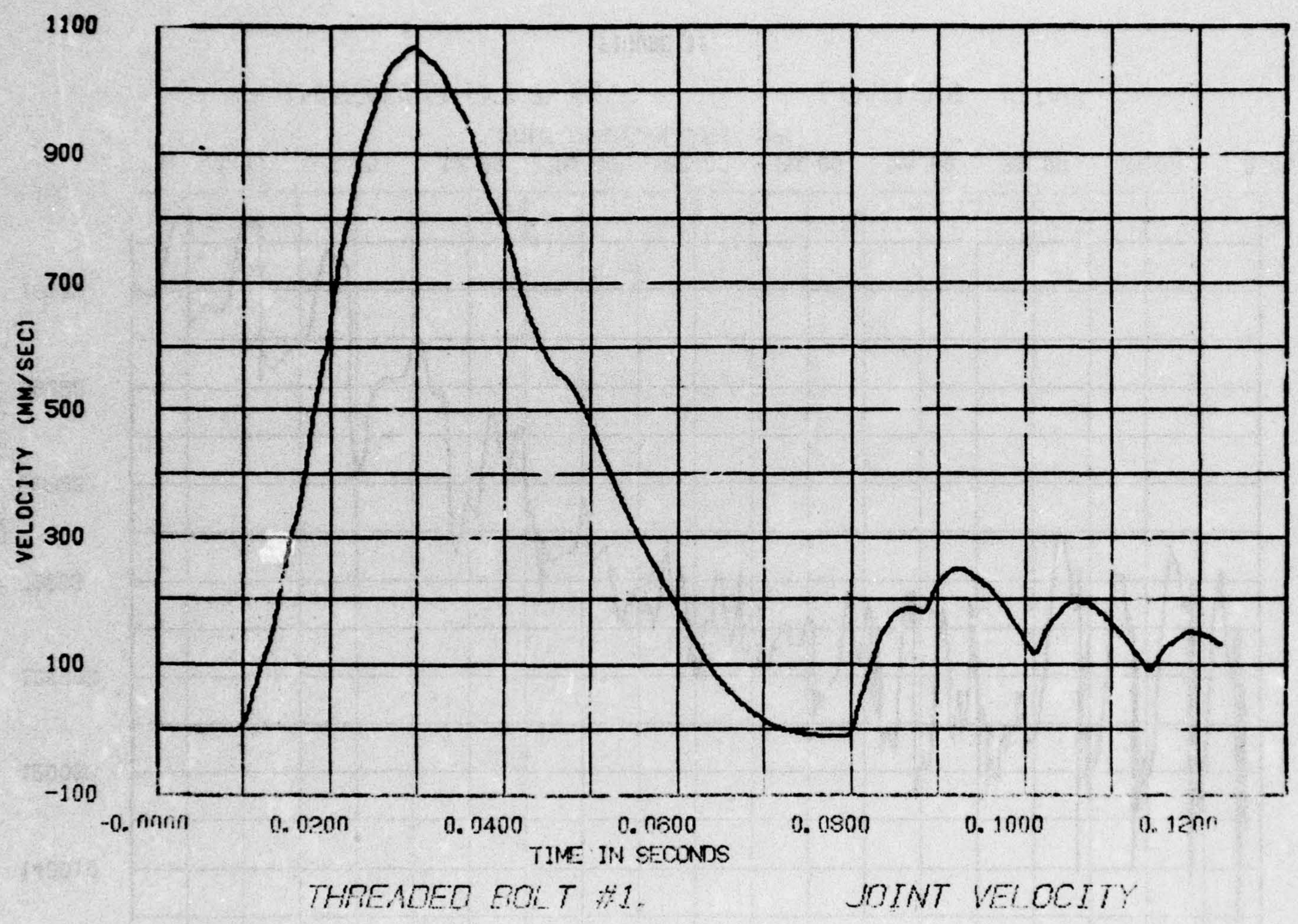
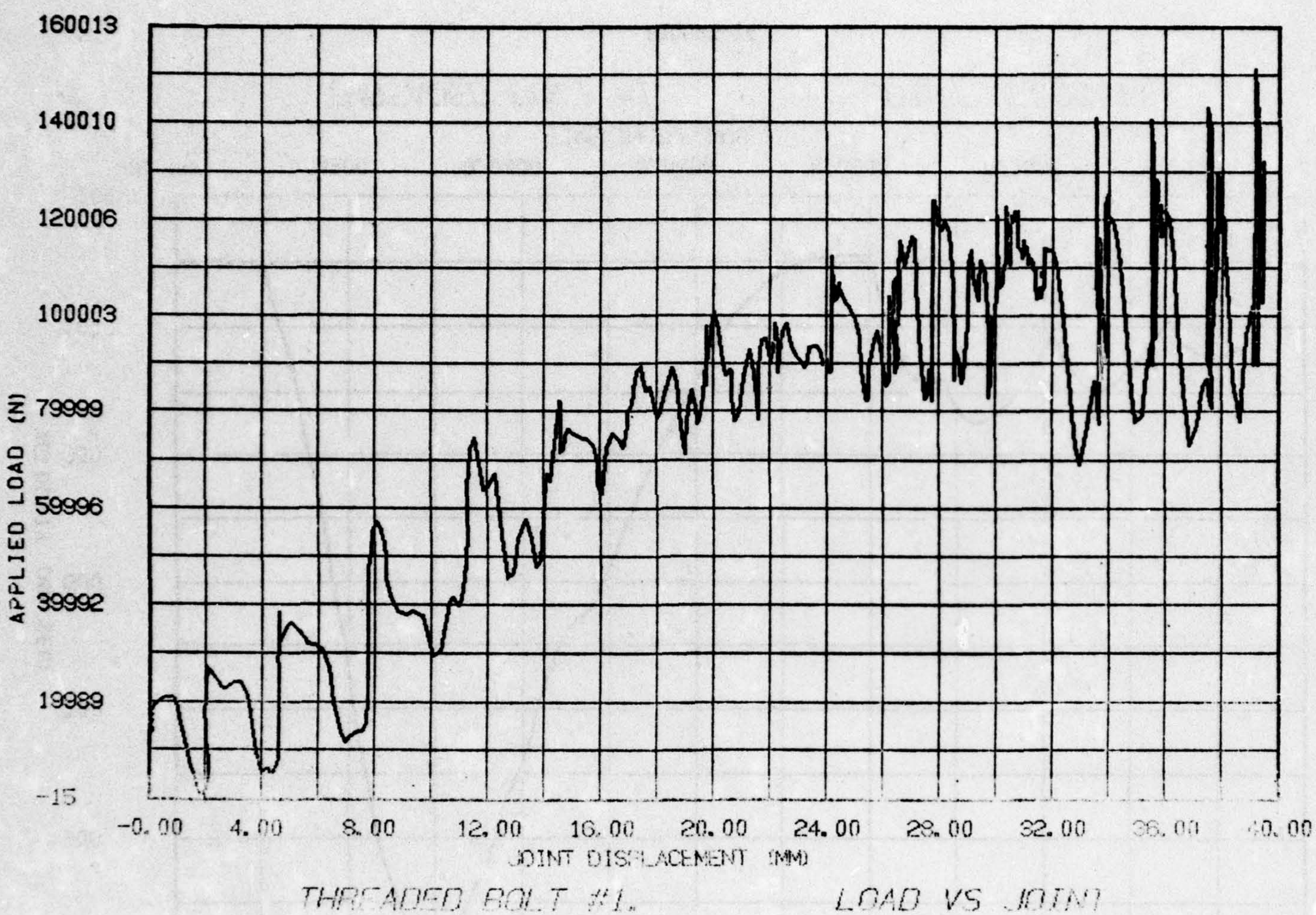
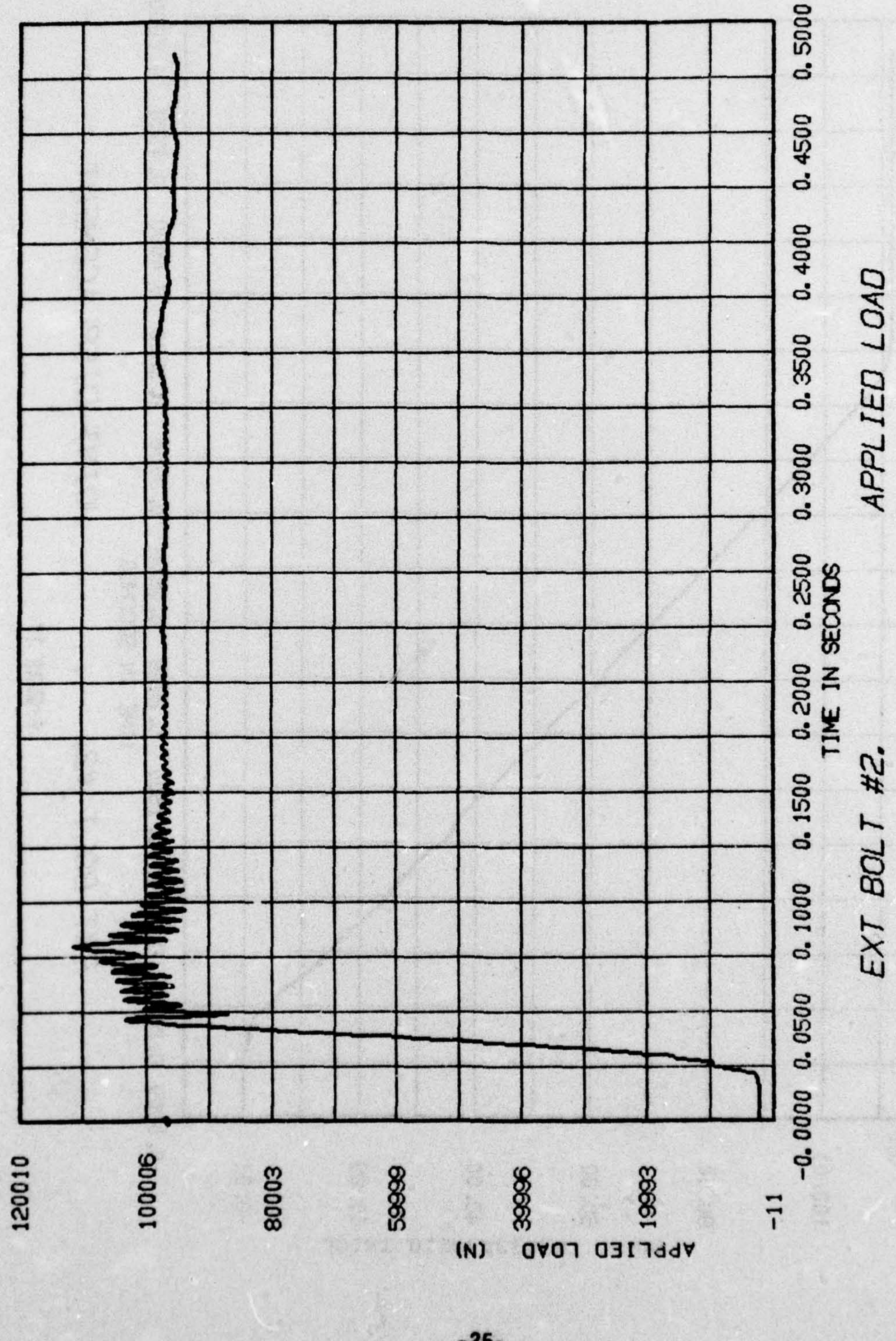

1100
900
700
500
300
100
-100
VELOCITY (MM/SEC)
-0.0000
0.0200
0.0400
0.0600
0.0800
0.1000
0.1200
TIME IN SECONDS
THREADED BOLT #1.
JOINT VELOCITY

FIGURE 14



APPLIED LOAD (N)
160013
140010
120006
100003
79999
59996
39992
19989
-15
-0.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
40.00
JOINT DISPLACEMENT (MM)
THREADED BOLT #1.
LOAD VS JOINT

FIGURE 15



EXT BOLT #2.
APPLIED LOAD
APPLIED LOAD (N)
120010
100006
80003
59999
39996
19993
-11
TIME IN SECONDS
-0.0000
0.0500
0.1000
0.1500
0.2000
0.2500
0.3000
0.3500
0.4000
0.4500
0.5000

FIGURE 16

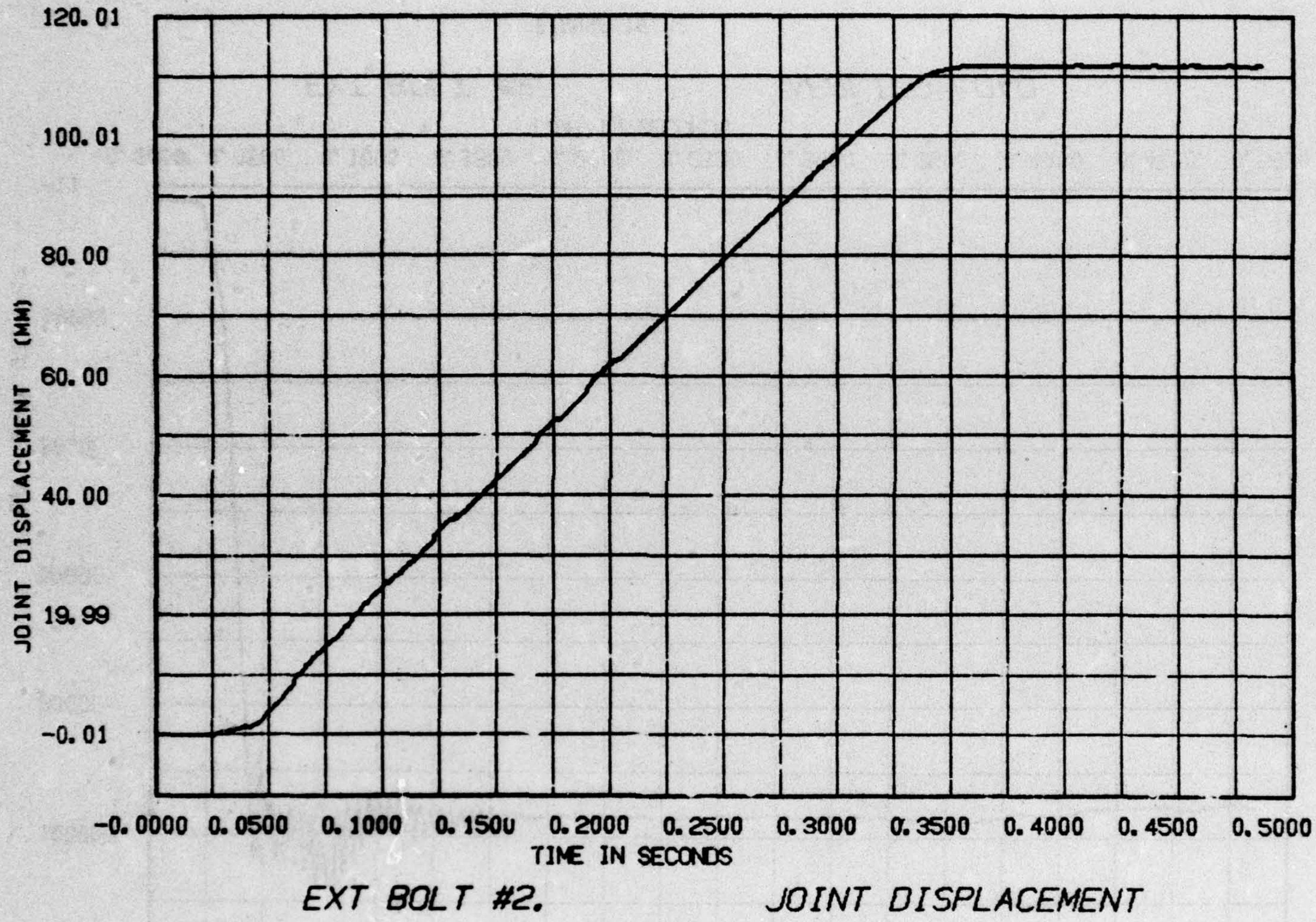
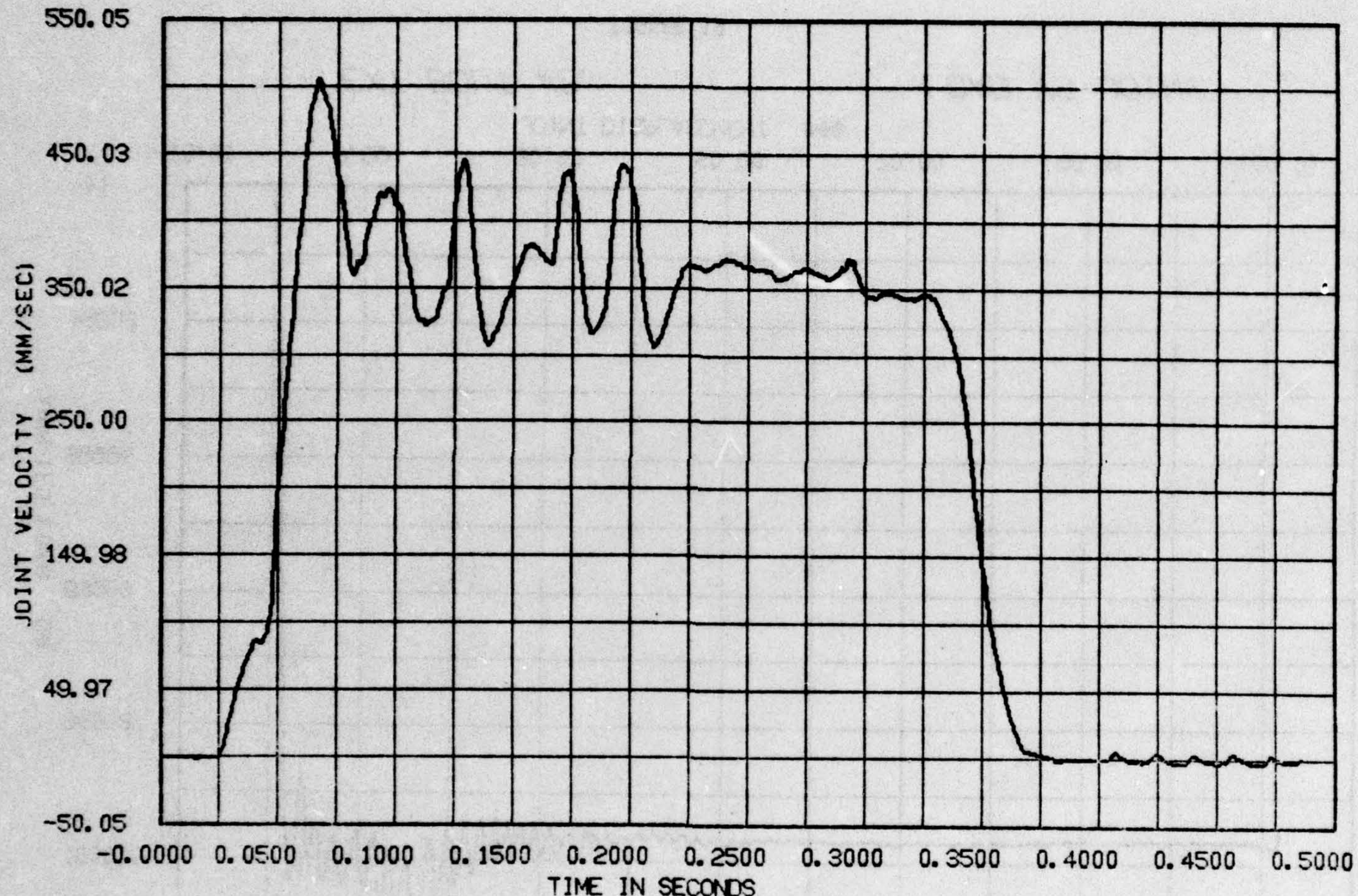
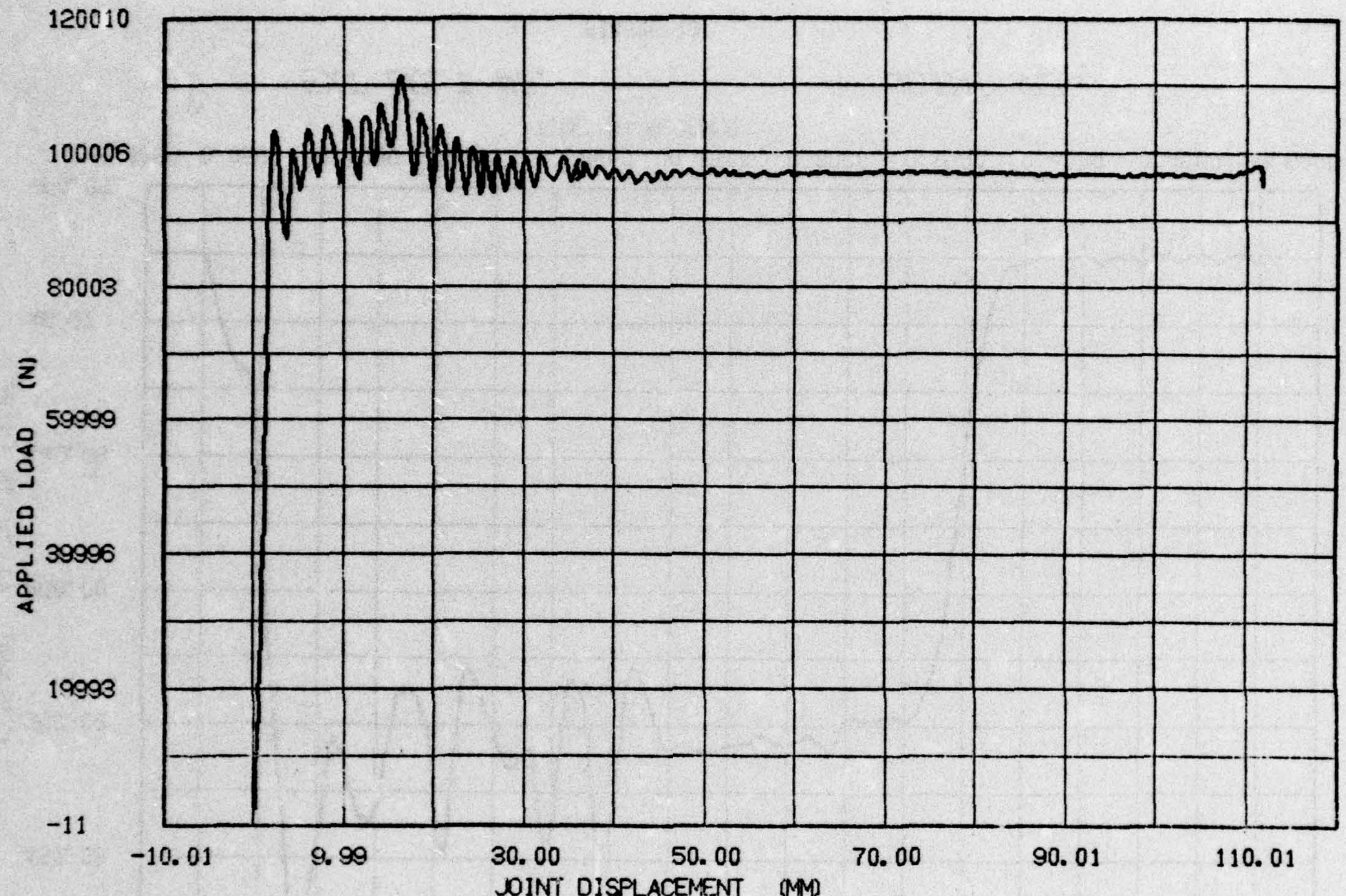

120.01
100.01
80.00
60.00
40.00
19.99
-0.01
JOINT DISPLACEMENT (MM)
-0.0000 0.0500 0.1000 0.1500 0.2000 0.2500 0.3000 0.3500 0.4000 0.4500 0.5000
TIME IN SECONDS
EXT BOLT #2.
JOINT DISPLACEMENT

FIGURE 17



EXT BOLT #2. *JOINT VEL.*

FIGURE 18



EXT BOLT #2, LOAD VS JOINT

FIGURE 19

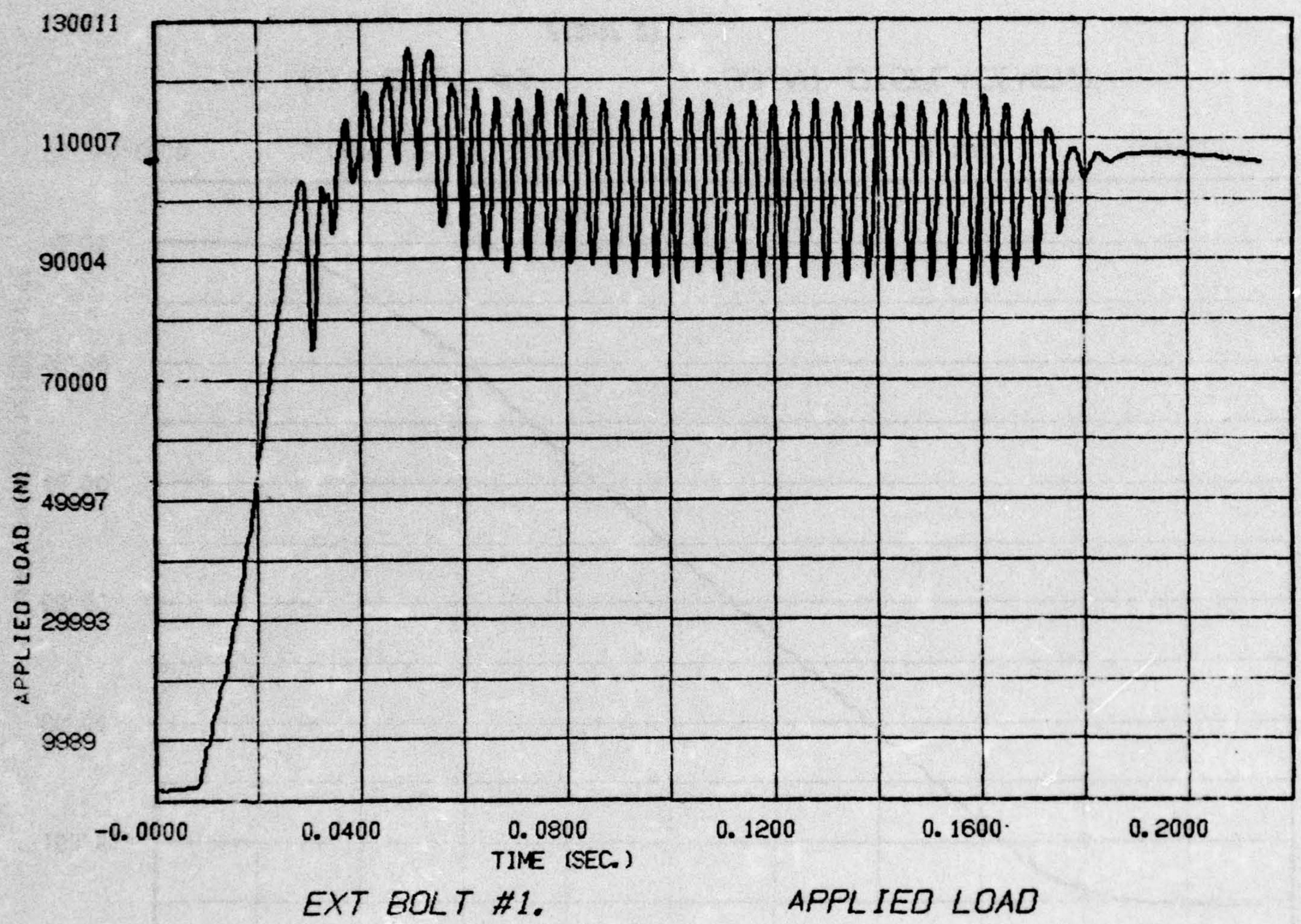

130011
110007
90004
70000
49997
29993
9989
APPLIED LOAD (N)
-0.0000
0.0400
0.0800
0.1200
0.1600
0.2000
TIME (SEC.)
EXT BOLT #1.
APPLIED LOAD

FIGURE 20

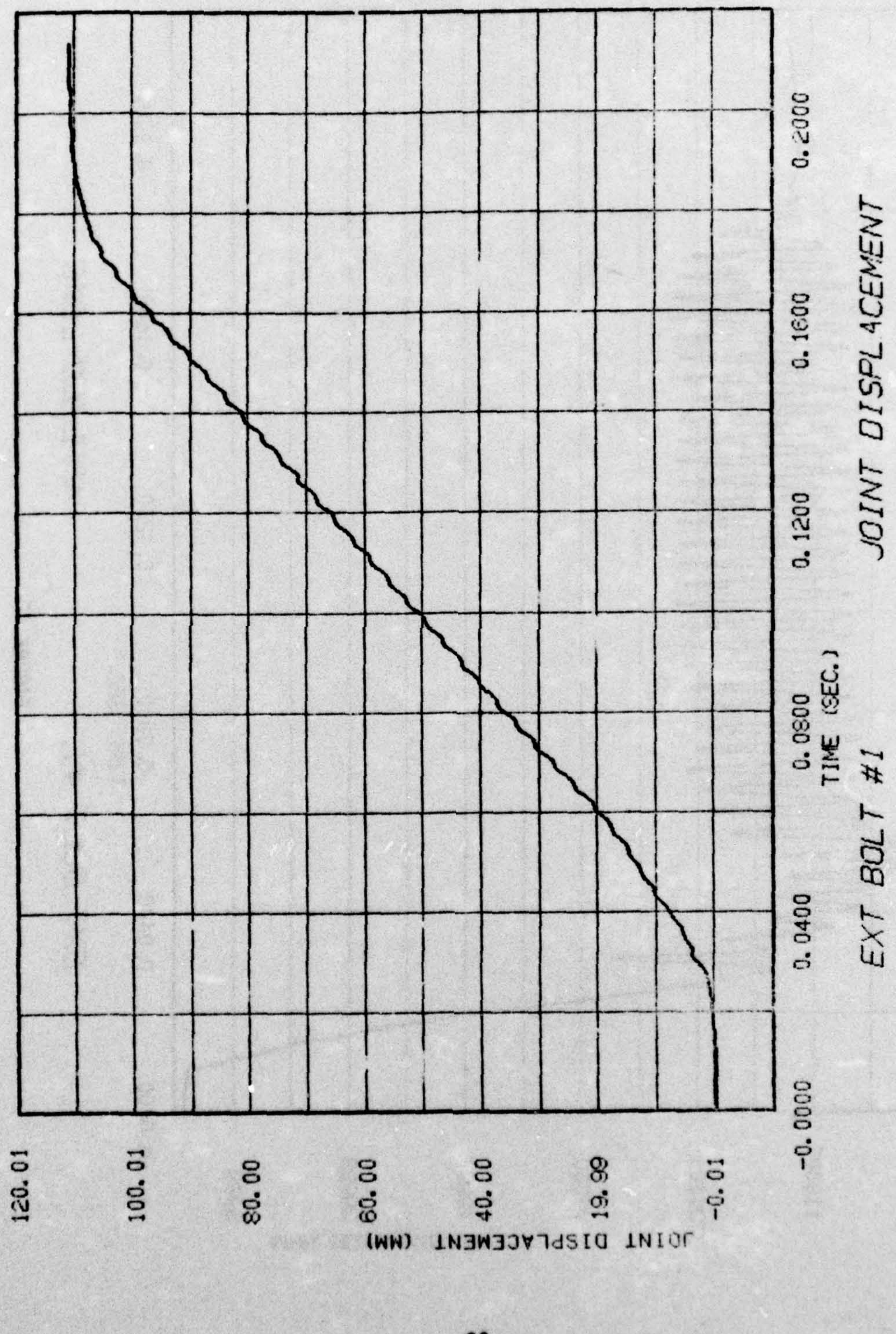

EXT BOLT #1 JOINT DISPLACEMENT
TIME (SEC.)
-0.0000
0.0400
0.0800
0.1200
0.1600
0.2000
JOINT DISPLACEMENT (MM)
120.01
100.01
80.00
60.00
40.00
19.99
-0.01

FIGURE 21

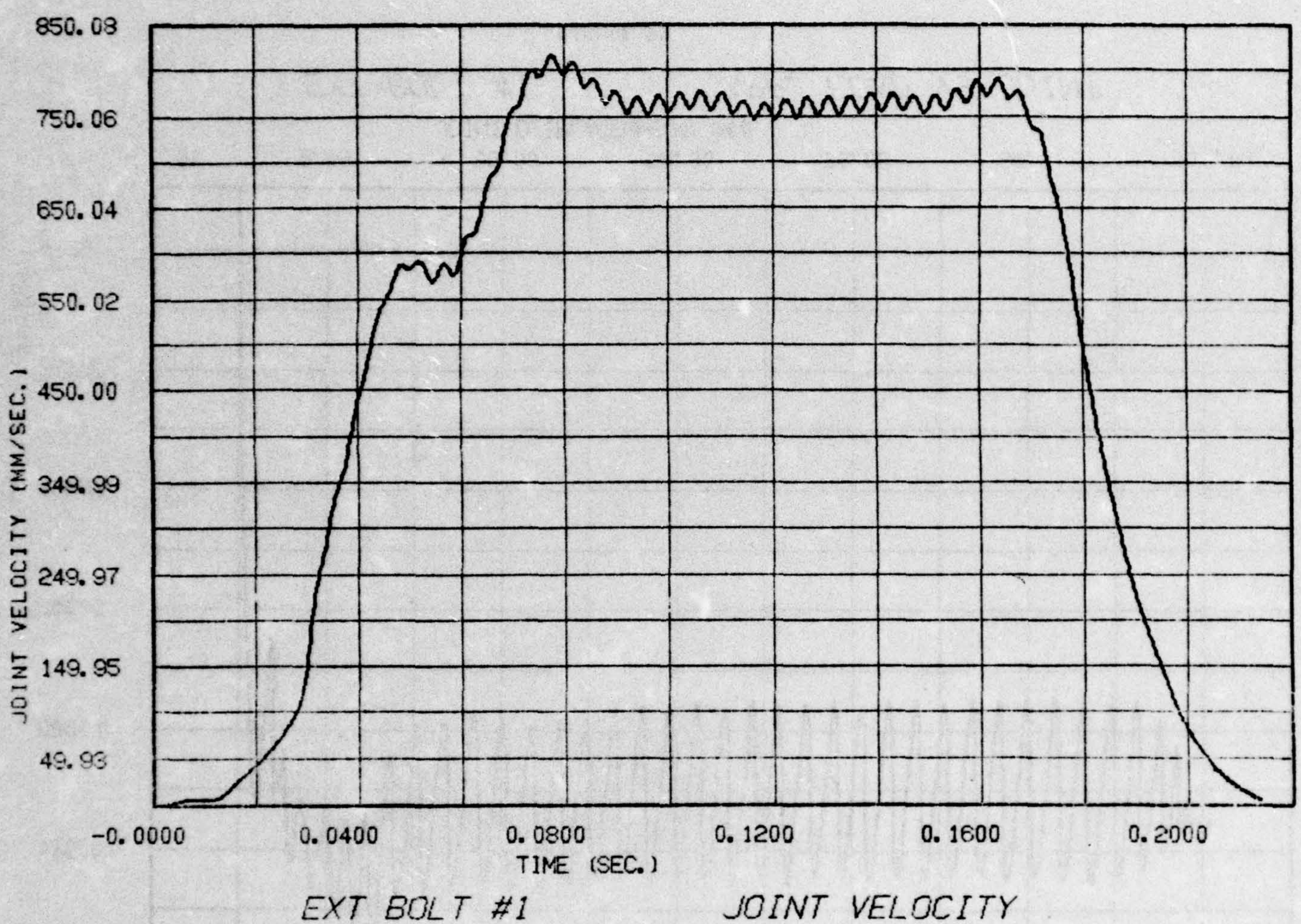

850.08
750.06
650.04
550.02
450.00
349.99
249.97
149.95
49.93
JOINT VELOCITY (MM/SEC.)
-0.0000
0.0400
0.0800
0.1200
0.1600
0.2000
TIME (SEC.)
EXT BOLT #1
JOINT VELOCITY

FIGURE 22

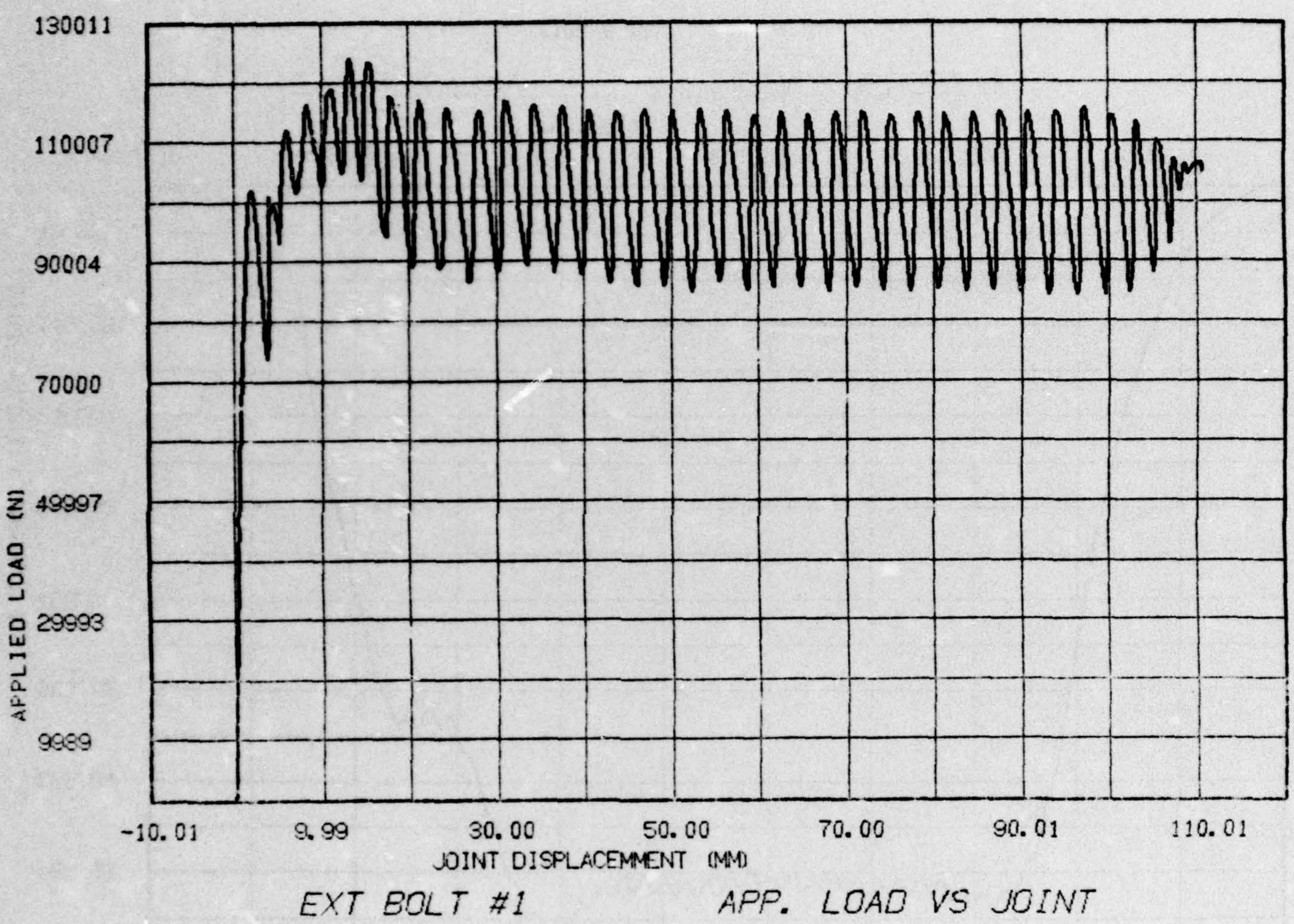

130011
110007
90004
70000
49997
29993
9989
APPLIED LOAD (N)
-10.01
9.99
30.00
50.00
70.00
90.01
110.01
JOINT DISPLACEMENT (MM)
EXT BOLT #1
APP. LOAD VS JOINT

FIGURE 23

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Miller, Wendell O

An evaluation of the design and applications of yieldable rock bolts, by Wendell O. Miller. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.

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Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.

Includes bibliographies.

1. Rock bolts. I. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report S-76-14)

TA7.W34 no.S-76-14