1963

Calibration of A325 bolts, Proc. ASCE, Vol. 89 (ST6) December 1963, Reprint No. 232 (63-18)

J. L. Rumpf

J. W. Fisher

LEHIGH UNIVERSITY INSTITUTE OF RESEARCH

LARGE BOLTED JOINTS

CALIBRATION OF A325 BOLTS

by
John L. Rumpf
John W. Fisher

Fritz Engineering Laboratory Report No. 288.5

CALIBRATION OF A325 BOLTS

by

John L. Rumpf

John W. Fisher

This work has been carried out as part of the Large Bolted Joints Project sponsored financially by the Pennsylvania Department of Highways, the Department of Commerce - Bureau of Public Roads, and the American Institute of Steel Construction. Technical guidance is provided by the Research Council on Riveted and Bolted Structural Joints.

Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

December 1962

Fritz Engineering Laboratory Report No. 288.5.

CALIBRATION OF A325 BOLTS

by

John L. Rumpf[1], M.ASCE and John W. Fisher[2], A.M.ASCE

SYNOPSIS

This report is a study of the behavior and performance of individual A325 high strength bolts. Direct tension and torqued tension tests of 170 A325 bolts are reported. Included are tests on regular and heavy head bolts. The regular head bolts ranged in size from 7/8 to 1-1/8 inches. Only 7/8 inch heavy head bolts were tested.

The tests show that the internal bolt tension can be related to readily observed quantities such as bolt elongation or turn-of-the nut.

1. INTRODUCTION

1.1 General

In structural joints connected with high strength bolts working loads are resisted by frictional forces acting on the faying surfaces of the connected material.

---

1 Professor of Civil Engineering, Drexel Institute of Technology, Phila., Pa.; formerly Research Instructor, Fritz Engineering Laboratory, Lehigh University

2 Research Associate, Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pa.

According to Coulomb's laws of static friction the value of the maximum frictional force is directly related to the normal force and to the surface condition as represented by the coefficient of static friction. In a bolted connection the normal force corresponds to the preload or clamping force of the bolts. A sort of average coefficient of friction can be calculated from tests of joints where the load causing slip equals the maximum frictional force and where the clamping force of each bolt is known through some calibration procedure.

When load is applied to a bolted connection the thickness of the gripped material may change thus permitting a change in the bolt tension. If the exact coefficient of friction at the instant of slip is desired one must know the history of each bolt tension as the joint is loaded because some bolts change length more than others depending on their locations in the joint. Because of the difficulties in devising equipment that can measure and record all bolt tensions at the instant of slip, investigators have reported coefficients based on the rather easily determined initial clamping force. Such coefficients have been called "apparent coefficient of friction", "nominal coefficients of friction" and "slip coefficient", in order to indicate their fictitious nature. Slip coefficient will be used in this paper. A slip coefficient determined from the slip load and initial clamping force may not compare directly with commonly used values of the static coefficient of friction as determined from sliding block tests.

1.2 Bolt Calibration Relationships

The tension in high strength bolts installed in structural joints can be estimated from controlled calibration tests. There are a number of readily observed quantities to which the internal tension may be related: torque, elongation, strain in the shank of the bolt, load cell output and turn-of-nut. Each relationship has advantages and disadvantages.

Tension vs. Torque Turning a nut against the resitance of gripped material elongates the bolt thus inducing an internal tension. The torque required to turn a nut depends upon the friction on the thread and on the bearing surface under the nut. It is possible to relate the induced tension and the applied torque as measured by a torque wrench, and a number of investigators have done so for the A325 high strength structural bolt[1,2,3,]. Because this relationship depends on the condition of the surface of the threads, nuts, and washers, considerable variation can occur in the bolt preload corresponding to any particular torque. Nevertheless, the 1954 specification of the Research Council on Riveted and Bolted Structural Joints[4] listed a table of equivalent torques as a guide to obtaining proper bolt tensions.

Experience in the field use of bolts has confirmed the erratic nature of the torque-tension relationship. The 1960 specification of the Research Council[5] abandoned the torque-tension table and in its place required that impact wrenches relying on torque control "...be calibrated by tightening, in a device capable of indicating actual bolt tension, not less than three typical bolts from the lot to be installed". This provision assumes that the thread condition of all bolts in a given lot is the same. To assure uniformity of friction on the bearing surface of the nut, a hardened washer is required when using a tightening method based on torque control. The same provision is retained in the 1962 specification[6]. When bolts from different lots are to be tightened the wrench must be recalibrated for each lot.

Despite the shortcomings of the torque type of control, an inspector must resort to it for want of a better method if he is required to check bolt tensions. The inspector's manual torque wrench must be calibrated in the same fashion as above[5,6].

<u>Tension vs. Elongation</u> A tension-elongation relationship has been used by many laboratory investigators. The method consists of applying a controlled load and measuring the resulting change in length of the bolt. With properly designed instruments and careful preparation of the bolts, accurate elongation readings can be obtained. If the bolt is to be tightened in the elastic range only, each bolt may be calibrated individually before installation in the connection[7]. If bolts are to be tightened into the inelastic range it is necessary to develop an average tension-elongation curve and assume that all bolts of that lot installed in a connection behave in the same fashion.

In field installations, it is not feasible to measure the initial and final length of each installed bolt and read the tension from the tension-elongation curve. The method usually has no practical value as a field control for bolt tension.

<u>Tension vs. Bolt Shank Strain</u> Electrical resistance strain gages mounted on the unthreaded shank of the bolt[9,10] have been used to calibrate bolts. This method is not feasible for structural joints because it requires the use of oversize holes or reduced diameter bolt shanks to provide clearance for the gages, and the bolt heads must have small holes drilled in them to accomodate the lead wires. If the shank is stressed into the inelastic range the gage becomes inoperative.

<u>Tension vs. Load Cell Output</u> A load cell is a cylindrical piece of steel through which the bolt is inserted. The load cell remains elastic under all conditions of load. Electrical resistance strain gages are mounted on the outside of the load cell rather than on the bolt shank.

The load cell has proven useful when studying bolt relaxation over a period of time[11]. If used to control tensions in bolted connections it would require bolts longer, by the length of the cell, then normally used for a given grip[12]. Thus, it is strictly a laboratory device.

Tension vs. Turn-of-nut As a nut is tightened against the resistance of the gripped material the bolt length within the grip is forced to elongate. If the gripped material and the threads were completely rigid, one complete turn of the nut would cause the bolt to elongate one pitch. This is not true because thread deformations do occur. However, it is possible to determine experimentally the relationships among the amount of rotation of the nut, the resulting elongation of the bolt, and the tension in the bolt.

The first turn-of-nut method used to install high strength bolts[13] advocated one full turn from finger tight. A subsequent version of this turn-of-nut idea[14] used either one-half or three quarters turn-of-nut from a "snug" position.

Controlling tension by the turn-of-nut is primarily a strain control, and the effectiveness of the method depends on the constancy of the starting point and the accuracy to which rotation increments are measured. If these factors are carefully controlled, desired tensions can be obtained with accuracy in both the elastic and inelastic ranges. In the inelastic region the load elongation curve is relatively flat and variations from lack of control of the starting point or the amount of nut rotation results in only minor tension variations.

1.3 Methods of Inducing Tension

To induce internal tension it is necessary to stretch the bolt in some way. This can be accomplished by subjecting the bolt to a direct axial load (direct tension) or, more commonly, to cause the bolt to elongate by turning the nut against the resistance of gripped material (torqued tension). The latter method is compatible with the field installation where bolts are usually tightened with a pneumatic impact wrench. The maximum tensions induced by this method are lower than the maximum tensions induced by a direct axial pull on the bolt.

The direct tension method is well suited for laboratory work where universal testing machines are available. The ASTM specification governing A325 bolts stipulates the direct tension type of acceptance test. Torqued calibration simulates conditions which are encountered in bolts installed in the field, and generally requires a specially designed bolt calibrator. Both procedures have been investigated in the tests reported herein.

2. MATERIAL PROPERTIES AND TESTING PROCEDURE

2.1 Description and Preparation of Bolts

Included in this study were ASTM A325 high strength bolts with regular and heavy semi-finished hexagon heads. All bolts had heavy semi-finished hexagon nuts. Quenched and tempered washers were placed under head and nut.

The regular head bolts included 7/8 in., 1 in. and 1-1/8 in. diameters ranging from 5-1/2 inches to 9-1/2 inches in length under the head. Thread lengths conformed to the requirements of the American Standards Association [15]. A few full-threaded and other non-standard bolts were tested. Several bolts had cut threads but most had rolled threads.

The heavy head bolts were 7/8 in. in diameter ranging from 5-1/4 inches to 9-1/2 inches in length under the head. All bolts had 1-1/2 inches of rolled thread, except the H lot which had 1-3/4 inches of thread.

Prior to testing, all bolts were identified by stamping a lot designation and a bolt number on the bolt head and shank ends. Holes were drilled in the center of the head and shank ends to accommodate the points of a C-frame extensometer. The holes were center drilled with a combination drill and countersink. The countersunk portion was between 1/32 in. and 1/16 in. deep. This provided a constant point of contact with the extensometer tips as the included angle of the countersunk portion of the center drilled hole was greater than the included angle of the extensometer points. Also, the point of contact between the bolt and the tips of the extensometer was the inside edge of the countersink and not the bottom of the hole.

This preparation of the bolt provided a protected measuring surface which could not be damaged during the impact bolting operation.

2.2 Testing Equipment and Instrumentation

A 300,000 lb. hydraulic universal testing machine was used to apply load during the direct tension phase of the study. Special grips were used to hold the bolt as shown in Fig. 1. The grips had center holes large enough for testing 1-1/8 in. bolts. Bushings were designed to modify this center hole to accommodate 1 in. and 7/8 in. diameter bolts with the usual clearance of 1/16 in.

The commercial bolt calibrator[16], shown in Fig. 2, was used during the torqued calibration series of tests. In actual field procedure a bolt is inserted in the device, being held in place by interchangeable bushings and plates so that one calibrator can be used to adjust wrenches for a number of different bolt sizes. Tightening the nut transmits pressure through a hydraulic load cell to a calibrated gage indicating bolt tension in pounds.

Contrary to usual field practice, the calibrator was used with the bolt in the vertical position in order to accommodate the C-frame extensometer used to measure elongation. Accuracy of readings was insured by checking the calibrator in a testing machine before and after testing

Bolt elongations were measured with the C-frame extensometer shown in Fig. 2. The device was capable of indiacting changes in length of 0.0001 inches. The tip of the dial plunger rested on the edge of the countersunk drilled holes. The pointed tip at the other end of the frame was threaded and provided with a knurled ring. The threaded screw and the adjustable plates enabled the device to accommodate a tip to tip length of 5 to 10 inches. A counterweight was attached so that the instrument would balance in the vertical position when mounted on a bolt. When measuring the initial and final lengths of bolts several readings were taken to establish the mean length.

Pneumatic impact wrenches were used during the torqued-calibration tests. Two sizes of wrenches were used. The larger sized wrench was capable of exerting more energy and was used to torque the 1-in. and 1-1/8 in. bolts. Hypodermic pressure gages were used to check the air pressure in the line at the wrench.

2.3 Testing Procedure

Direct Tension Calibration The procedure used during direct tension testing was as follows: The bolt to be calibrated was inserted in the special tension grips in the hydraulic testing machine and the position of the testing machine head set so that, at the required grip, the nut was only finger tight and the bolt was unstressed. Zero readings of bolt length were taken with no load on the bolt. Load was then applied to the specimen in five-kip increments until the specified proof load of the bolt was reached. At this point load was removed in decrements to zero. The bolts were then measured a second time at zero load to insure that the variation of zero readings did not exceed the specification maximum of 0.005 in. Having checked the proof load requirements, testing was resumed with similar increments of load while in the elastic range; elongation increments were used for the remainder of the test. The load was applied at a rate of 0.005 in./min. throughout the test.

The testing machine was stopped in the inelastic region and a few minutes were allowed to elapse to enable the load to decrease to the minimum value. This decrease was found to be reasonably constant and was approximately one kip. Hence, the effect of strain rate was negligible in these tests.

<u>Torqued Calibration</u> The objective of this series of tests was

to establish tension-elongation relationships caused by turning the nut rather than by pulling the bolt in direct tension. The bolts were inserted in the commercial calibrator, and the nut tightened until an initial load of 8 kips was reached. Initial lengths were then measured with the extensometer. Using an impact wrench, the nut was rotated in 45 degree increments. Load and elongation readings were recorded at each increment until failure was imminent. Since the readings were taken after the impact wrench was removed from the nut, dynamic effects were excluded.

Additional tests were conducted during which an impact wrench was used to continuously turn the nut a predetermined rotation increment. Rotations of 1/2 turn, 1 turn and 1-1/2 turn were chosen. The results were compared with those obtained from 45 degree increments of turn.

Special Tests A special series of tests were conducted to determine the reserve tensile strength of a torqued bolt. The bolt was placed in the commercial calibrator and given a specified nut rotation. (Load, elongation and turn-of-nut readings were taken.) At this point, a hydraulic hand pump connected to the commercial calibrator was jacked and a direct axial load was applied to the bolt through the hydraulic system of the calibrator. During this procedure, readings of load were taken at selected increment of elongation. The test set up is shown in Fig. 3.

An additional torque calibration program was designed to investigate the possibility of re-using high strength bolts which had been tightened previously by turning the nut one-half turn. A 7/8 in. diameter bolt was torqued in 45 degree increments of rotation from a snugging load of 8 kips. Load and elongation readings were taken at each increment. After being tightened one-half turn from the snug position, the rotation of the nut was reversed and load removed to simulate the removal of a bolt in the field. After all load had been removed, the snugging load was reapplied and the nut was once more rotated through one-half turn. This procedure was repeated over and over again. Load and elongation readings were recorded throughout.

This same method was used to test both regular and heavy head bolts.

3. TEST RESULTS

The test results are summarized in Tables 1, 2 and 3. The tables show the mean ultimate load and rupture loads with their associated elongations. Also shown are the standard deviations to give a measure of the dispersion associated with each mean. According to statistical theory, two-thirds of the test data are within plus or minus one standard deviation of the mean.

Sixty-four regular head bolts having rolled threads were tested. Of these, 38 were tested in direct tension and 26 in torqued tension. The results are given in Table 1. The tests included three diameters of bolts, 7/8 in. 1 in. and 1-1/8 in.

The bolts of the Q-W lots were regular head and had cut threads. These bolts were from the same steel and heat treatment. Different letter designations were used to differentiate between various lengths of bolts and threads. Altogether, 42 of these bolts were tested; 21 in direct tension and 21 in torqued tension. The results of these tests are given in Table 2. Only 7/8 in. diameter bolts were tested.

Four different lots of 7/8 in. heavy head bolts were tested. Altogether seventy five bolts were tested, 31 in direct tension, 29 in torqued tension, 12 in combined torque and direct tension, and 3 by repeated applications of 1/2 turn. The results for the direct tension and torqued tension tests are given in Table 3.

Figure 4 shows a typical mean load elongation curve for five 7/8 in. heavy head bolts from the same lot tested in direct tension. The curve was drawn through mean points that were established for groups at approximately the same elongation increment. The results of typical torqued calibration tests for the same lot of 7/8 in. heavy head bolts. The scatter of data associated with the bolts in a particular lot is readily observed in Figs. 4 and 5.

The results of combined direct tension and torqued tension tests are shown in Fig. 6. Bolts were first tensioned by turning the nut either 1/2 or 2/3 of a turn. Additional load was then applied by direct tension.

Bolts with regular heads and ASA standard lengths of thread ruptured on a transverse plane through the root of the thread. But, many of the heavy head bolts and several regular head bolts, that were purposely furnished with strengths near the ASTM A325 minimum, failed by thread stripping. The regular head bolts that stripped had lengths of thread between the nut and thread run out comparable to those on the heavy head bolts.

A number of factors accounted for the thread stripping. Among these were the minimum strength material, the nut engaging the thread run out, and the necking which took place in the threaded portion. These factors undoubtedly precipitated thread stripping.

Several bolts were torqued continuously to 1/2 turn, 1 turn and 1-1/2 turns respectively from the "snug" position in the bolt calibrator. The load and elongations which were obtained were compared to the torqued calibration curve obtained by 45 degree increments of turns. The correlation between the two methods is shown in Fig. 7 where the continuously torqued bolts are compared with the mean incrementally torqued calibration curve.

The results of the repeated application of one-half turn of the nut is shown in Fig. 8 for one heavy head bolt.

4. ANALYSIS OF RESULTS

4.1 Direct Tension vs. Torqued Tension Calibration

The mean curves from Figs. 4, 5 and 6 are replotted in Fig. 9. No appreciable difference exists between the direct tension and torqued calibration, load-elongation relationships in the elastic range. All lots of bolts including both the regular and heavy head showed a linear behavior in the elastic range.

Beyond the proportional limit, the relationship between internal bolt tension and elongation was different. Both the ultimate strength and elongation at rupture were greater for the direct tension tests. The strength ranged from 5 to 25 percent more than for comparable torqued tension tests of bolts of the same lot. The elongations at rupture for bolts tested by torquing were from 20 to 60 percent less than the rupture elongations recorded during the direct tension tests.

The reduction in ultimate strength and elongation at rupture results from the different stress condition present when the bolt is tensioned by turning the nut. Frictional resistance between the nut and bolt threads produces torsional shearing stresses. The resulting combined stress state influences the tension-elongation relationship. Evidently, the frictional resistance between the bolt and nut threads becomes critical when the material of the threaded portion of the bolt is stressed beyond the proportional limit and takes on inelastic deformations which cause thread binding between the nut and bolt. Below the proportional limit, thread deformations are small and the tension-elongations show no appreciable difference for the two methods.

4.2 Reserve Strength

Once installed the high strength bolt may be subjected to direct tension loads. It is of interest then to determine the behavior of a bolt installed by torquing and then subjected to direct tension. This can be seen in Fig. 9 where the combined test is compared with the individual direct tension and torqued tension curves. When direct tension is applied to the torqued bolt, the ultimate tensile strength is at least equal to that obtained from the direct tension tests.

4.3 Effect of Grip

The mean load-elongation curves for fifteen regular head 7/8 in. bolts of various grips are plotted in Fig. 10. These bolts were made from the same material and heat treatment. The thickness of the gripped material varied from 4-3/4 inches to 6-3/4 inches. However, the length of thread under the nut varied only from 3/4 to 1 inches.

An examination of Fig. 10 indicates that no systematic variation existed among the load-elongation relationships for the different grip conditions. Apparently as long as the length of thread under the nut is relatively constant, grip has no appreciable effect on these relationships.

Figure 10 shows that within the elastic range the elongation increases slightly with an increase in grip. As the load is increased beyond the proof load, the threaded portion, which is approximately a uniform length, behaves plastically while the shank remains essentially elastic. The inelastic deformation is reasonably uniform beyond proof load and overshadows the small elastic elongations that occur in the bolt shank. As a result grip length has little effect on the load elongation relationship beyond the proportional limit.

The behavior shown in Fig. 10 for the direct tension test was also observed during the torqued tension tests.

Heavy head bolts demonstrated similar behavior for grips ranging from 4 to 8 inches and with thread lengths under the nut from 1/8 to 3/8 inches.

4.4 Effect of Thread Length

Since most of the elongation occurs in the threads, the length of thread between the thread run out and the face of the nut will affect the load-elongation relationship. That this is true can be noted in Tables 1, 2 and 3 by comparing the mean elongations at ultimate load and rupture for bolts having different lengths of thread under the nut.

The number of turns to failure from the torqued tension tests are plotted as a function of the thread length under the nut in Fig. 11. Both regular head and heavy head bolts are shown. Fig. 11 shows that a decrease in thread length is accompanied by a decrease in the turns to failure. This was observed for both the torqued tension and direct tension tests. No appreciable difference was observed between the regular and heavy head bolts as long as the length of thread under the nut was the same. With 1/8 in. of thread under the nut, failure occurred at approximately one and one-half turns of the nut. The amount of thread under the nut ranges between 1/8 in. to 9/16 in. for 7/8 in.

The failures shown in Fig. 12 indicate clearly the zone of plastic deformation during the tension tests. The bolts shown are from lots Q, R and S that had cut threads and regular heads. The full threaded bolt necked throughout the entire threaded length. In the bolts with lesser amounts of thread, appreciable necking has taken place only in the threaded portion.

The heavy head bolt with short thread length is compared to the regular head bolt with ASA standard thread length in Fig. 13. Also shown are the zones indicating the range of elongation for 1/2 and 1 turn of the nut. The shorter length of thread under the nut of the heavy head bolts results in a decrease in the elongation capacity. The regular head bolts with the ASA standard thread length fractured at 2 to 3 turns from the snug position. The heavy head bolts with the shorter thread length fractured at 1-1/2 to 1-3/4 turns from snug. At this number of turns the nut had not yet engaged the thread run out.

The elongations corresponding to 1/2 and 1 turn of the nut were approximately the same for the regular and heavy head bolts.

4.5 Clamping Force

Bolts tensioned by turning the nut 1/2 turn or more are preloaded well above the specified proof load and the proportional limit as indicated in Figs. 5, 7 and 13. Bolts elongated beyond the proportional limit have a reasonably uniform preload as considerable variation in elongations produces little variation in bolt tension.

The load-elongation relationship for bolts tensioned by torquing can be compared to the ideal elastic-plastic relationship that is associated with structural steel. In the elastic portion small changes in elongation result in large changes in load and in the plastic portion additional elongation produces no increase in load. From this comparison and by observing the relationship shown in Fig. 5 it can be seen readily that little increase in preload is obtained by giving the nut additional rotation from the 1/2 turn position.

The clamping force for both regular and heavy head bolts is nearly the maximum obtainable when the nut is given approximately one-half turn of rotation. Further rotation decreased the rotational factor of safety against twisting off without adding appreciably to the clamping force.

4.6 Re-Use of High Strength Bolts

Several 7/8 inch A325 bolts were tested by alternately torquing one-half turn, loosening and retorquing. The record of one such test is shown in Fig. 8. The heavy head bolt was given one-half turn from the snug position in 45 degree increments four times and failed after 1/4 turn during the fifth time. The cumulative plastic deformations caused a substantial decrease in the bolt's deformation capacity with each succeeding half turn.

However, the tests have demonstrated that re-using a high strength bolt tightened to 1/2 turn does not reduce the potential clamping force. This is true for both regular and heavy head bolts. The regular head bolts were able to withstand two or more additional half-turns than the heavy head bolts[18].

5. CONCLUSIONS

1. The maximum tension and elongation in a bolt obtained by pulling the bolt in direct tension is greater than that obtained when the nut is turned against the resistance of the gripped material. Tests on 170 A325 bolts showed the ultimate strength in direct tension was 5 to 33 percent higher than the ultimate strength in torqued tension. The maximum elongation was approximately 100 percent greater.

2. Bolts with strengths slightly above minimum specified tensile strength and up to 125 percent of it had similar elongation characteristics.

3. No appreciable difference was found in the clamping force and elongation between bolts torqued continuously and

those torqued in 45 degree increments to the same total rotation.

4. Bolts installed by torquing can sustain additional direct tension loads without any apparent reduction in their ultimate tensile strength as given by the direct tension relationship.

5. Grip length has no appreciable effect on the load-elongation characteristics of high strength bolts beyond the proportional limit as long as the length of thread under the nut is approximately the same. Beyond the proportional limit, most of the elongation of the bolt takes place in the free threads under the nut.

6. Nut rotations greater than one-half turn from snug are not necessary for the longer grip bolt as little is gained in additional clamping force. In fact, the additional rotation causes an appreciable decrease in the rotational factor as safety especially for heavy head bolts.

7. A lesser amount of exposed thread under the nut results in a decrease in the deformation capacity of the high strength bolt. This holds for both regular and heavy head bolts.

8. The heavy head bolt has a short thread length whereas the regular head bolt has the ASA thread length(15). As a result, for a given thickness of gripped material the heavy head bolt has less deformation capacity. Nevertheless, the tests showed that the heavy head bolt was able to sustain at least one and one-half turns of the nut from the snug position with 1/8 in. thread under the nut.

9. In these tests the rotational factor of safety against twisting off the bolt was at least three half-turns for the heavy head bolt and four to six half-turns for the regular head bolt. In other words, heavy head bolts given one-half turn-of-nut have sufficient deformation capacity to sustain two additional half turns before failure. The regular head bolts can sustain three to five additional half-turns.

10. One-half turn-of-nut produces consistent bolt tensions in the inelastic range. Bolts tightened to one-half turn of the nut from snug developed 85 to 95 percent of the available torqued tension strength. The snugging load was taken as eight kips.

11. Limited tests have indicated that high strength bolts which have previously been given one-half turn-of-nut can be reused if the prior history is known.

6. ACKNOWLEDGEMENTS

This study was carried out at the Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania.

The project is sponsored financially by the Pennsylvania Department of Highways, the Department of Commerce--Bureau of Public Roads and the American Institute of Steel Construction. Guidance is provided by the Research Council on Riveted and Bolted Structural Joints.

The authors wish to acknowledge the contributions of all those who were connected with various phases of the investigation. Dr. L. S. Beedle served as project director; Messrs. R. T. Foreman, R. A. Bendigo, S. E. Dlugosz and P. O. Ramseier helped conduct the tests; and the members of the advisory sub-committee (E. J. Ruble, Chairman) gave guidance and advice. Messrs. S. J. Errera and K. R. Harpel and their staff of technicians aided in conducting the investigation.

The fabricated steel construction department of Bethlehem Steel Co., particularly Messrs: E. F. Ball, K. de Vries and J. J. Higgins gave much consideration to this

work. Messrs. W. R. Penman and A. Schwartz of the Lebanon Plant of Bethlehem Steel Company furnished the bolts.

7. LIST OF REFERENCES

1. C. Batho, E. H. Bateman
   INVESTIGATIONS ON BOLTS AND BOLTED JOINTS,
   Steel Structures Research Committee Report,
   1931

2. G. A. Maney
   WHAT HAPPENS WHEN A BOLT IS TWISTED OFF?
   Fasteners, Vol. 3, No. 1, 1946

3. W. H. Munse, D. T. Wright, N. M. Newmark
   LABORATORY TESTS OF HIGH TENSILE BOLTED
   STRUCTURAL JOINTS,
   Transactions ASCE, Vol. 120, 1955.

4. Research Council on Riveted and Bolted Structural
   Joints of the Engineering Foundation
   SPECIFICATIONS FOR THE ASSEMBLY OF STRUCTURAL
   JOINTS USING HIGH STRENGTH BOLTS,
   1954

5. Research Council on Riveted and Bolted Structural
   Joints of the Engineering Foundation
   SPECIFICATIONS FOR STRUCTURAL JOINTS USING
   ASTM A-325 BOLTS,
   1960.

6. Research Council on Riveted and Boltes Structural
   Joints of the Engineering Foundation
   SPECIFICATIONS FOR STRUCTURAL JOINTS USING
   ASTM A-325 BOLTS,
   Proceedings of ASCE, Vol. 88, ST5, 1962

7. R. A. Hechtman, D. R. Young, A. G. Chin, E. R. Savikko
   SLIP OF JOINTS UNDER STATIC LOAD,
   Transactions ASCE, Vol. 120, 1955.

8. R. T. Foreman, J. L. Ru mpf
   STATIC TENSION TESTS OF COMPACT BOLTED JOINTS,
   Transactions ASCE, Vol. 126, Part II, 1961.

9. G. A. Maney
BOLT STRESS MEASUREMENTS BY ELECTRIC STRAIN GAGES,
Fasteners, Vol. 2, No. 1, 1945.

10. K. S. Petersen, W. H. Munse
STATIC TENSION TESTS OF RIVETED AND HIGH STRENGTH BOLTED STRUCTURAL CONNECTIONS,
University of Illinois Engineering Experiment Station, Structural Research Series No. 124, November 1954

11. C. W. Lewitt, E. Chesson Jr., W. H. Munse
PRELIMINARY REPORT ON RELAXATION STUDIES OF HIGH STRENGTH BOLTS,
University of Illinois Experiment Station, October 1959

12. R. L. Sanks, C. C. Rampton, Jr.
GRIT AND SHOT-REINFORCED HIGH TENSILE BOLTED JOINTS,
Proceedings of ASCE, Vol. 83, ST6, 1954

13. F. P. Drew
TIGHTENING HIGH-STRENGTH BOLTS,
Proceedings of ASCE, Vol. 81, August 1955

14. E. F. Ball, J. J. Higgins
INSTALLATION AND TIGHTENING OF HIGH STRENGTH BOLTS,
Transactions ASCE, Vol. 126, Part II, 1961

15. American Standards Association
SPECIFICATIONS FOR SQUARE AND HEXAGON BOLTS AND NUTS B18.2, 1955

16. THE SKIDMORE-WILHELM BOLT TENSION CALIBRATOR
Skidmore-Wilhelm Bulletin 110, 1956

17. R. A. Bendigo, J. L. Rumpf
STATIC TENSION TESTS OF LONG BOLTED JOINTS,
Lehigh University, Fritz Engineering Laboratory Report No. 271.8, February 1960

18. R. A. Bendigo, J. L. Rumpf
CALIBRATION AND INSTALLATION OF HIGH STRENGTH BOLTS,
Lehigh University, Fritz Engineering Laboratory, Report No. 271.7, September 1959

TABLE 1

REGULAR HEAD BOLTS WITH ROLLED THREADS

		B-Lot	C	D	D	Z	A	Y	G
Size (Nominal Diameter)	in.	7/8	7/8	7/8	7/8	7/8	1	1	1-1/8
Length Under Head	in.	5.5	9.5	5.5	5.5	5.5	5.5	5.5	6.0
Thread Length	in.	2	2.25	2	2	2	2.25	2.25	2.50
Grip Length +	in.	4.25	8.25	4.25	3.80	4.25	4.25	4.25	4.25
Thread Length in Grip	in.	0.75	1.00	0.75	0.30	0.75	1.00	1.00	0.75
Stress Area	sq.in.	0.462	0.462	0.462	0.462	0.462	0.606	0.606	0.763
Proof Load	kips	36.05	36.05	36.05	36.05	36.05	47.25	47.25	56.45
Minimum Ultimate Load	kips	53.2	53.2	53.2	53.2	53.2	69.7	69.7	80.1

DIRECT TENSION CALIBRATION

		B-Lot	C	D	D	Z	A	Y	G
Number of Specimens Tested		5	5	5	0	8	5	5	5
Mean Ultimate Load	kips	54.3	53.3	56.9	-	60.4	73.7	73.1	91.2
Standard Deviation	kips	1.22	0.30	0.55	-	2.45	0.96	0.94	1.91
% of Min. Ult. Load	%	102.1	100.0	107.0	-	113.5	105.7	104.9	113.9
Mean Rupture Load	kips	45.2	45.2	45.8	-	49.0	63.2	62.5	76.6
Standard Deviation	kips	1.89	1.05	1.15	-	4.19	2.49	1.77	3.15
Mean Elong. Proof Load	in.	0.010	0.023	0.010	-	0.010	0.011	0.011	0.010
Standard Deviation	in.	0.0001	0.0050	0.0001	-	0.0003	0.0002	0.0008	0.0003
Mean Elong. Ult. Load	in.	0.134	0.230	0.128	-	0.135	0.184	0.220	0.200
Standard Deviation	in.	0.0370	0.0231	-	-	-	0.0050	-	-
Mean Elong. Rupt. Load	in.	0.31	0.31	0.27	-	0.24	0.36	0.39	0.30
Standard Deviation	in.	0.047	0.044	0.050	-	0.040	0.030	0.033	-

TORQUE TENSION CALIBRATION

		B-Lot	C	D	D	Z	A	Y	G
Number of Specimens Tested		3	3	4	3	8	3	0	2
Mean Ultimate Load	kips	45.7	45.8	51.1	50.9	55.4	56.0	-	75.7
Standard Deviation	kips	0.85	0.51	0.765	2.68	1.84	2.00	-	2.48
% of Min. Ult. Load	%	87.20	86.3	95.9	95.7	104.1	80.3	-	94.5
Mean Rupture Load	kips	38.5	34.3	40.5	47.1	47.9	47.9	-	66.0
Standard Deviation	kips	2.00	4.01	0.58	0.62	1.74	2.69	-	-
Mean Elong. Proof Load	in.	0.009	0.034	0.010	0.009	0.009	0.017	-	0.012
Standard Deviation	in.	0.0002	0.0016	0.0012	-	0.0010	0.0043	-	0.0005
Mean Elong. Ult. Load	in.	0.072	0.087	0.069	0.052	0.076	0.060	-	0.077
Standard Deviation	in.	0.0067	0.0102	0.0112	0.0129	0.0118	0.0079	-	0.020
Mean Elong. Rupt. Load	in.	0.17	0.21	0.20	0.10	0.16	0.12	-	0.15
Standard Deviation	in.	0.014	0.021	0.036	0.027	0.017	0.011	-	-

---

+Grip length is defined as the distance between the inside faces of the bolt head and the nut

TABLE 2

REGULAR HEAD BOLTS WITH CUT THREADS

		Q-Lot	R	S	T	U	V	W
Size (Nominal Diameter)	in.	7/8	7/8	7/8	7/8	7/8	7/8	7/8
Length Under Head	in.	5.5	5.5	5.5	6.5	7	7.5	8.5
Thread Length	in.	2.25	3.25	5.5	2.25	2.25	2.25	2.25
Grip Length +	in.	4.25	4.25	4.25	5.00	5.50	6.25	7.00
Thread Length in Grip	in.	1.0	2.0	4.25	0.75	0.75	1.0	0.75
Stress Area	sq.in.	0.462	0.462	0.462	0.462	0.462	0.462	0.462
Proof Load	kips	36.05	36.05	36.05	36.05	36.05	36.05	36.05
Minimum Ultimate Load	kips	53.2	53.2	53.2	53.2	53.2	53.2	53.2

DIRECT TENSION CALIBRATION

Number of Specimens Tested		3	3	3	3	3	3	3
Mean Ultimate Load	kips	53.9	52.2	53.8	54.8	55.2	53.8	55.2
Standard Deviation	kips	0.14	0.09	0.52	1.04	0.72	0.51	0.95
% of Min. Ult. Load	%	101.3	98.1	101.1	103.0	103.8	101.1	103.8
Mean Rupture Load	kips	42.0	35.0	43.3	45.3	46.7	45.9	46.7
Standard Deviation	kips	2.64	--	1.45	0.52	1.60	1.21	1.16
Mean Elong. Proof Load	in.	0.012	0.018	0.021	0.014	0.015	0.016	0.017
Standard Deviation	in.	0.0005	0.0008	0.0025	0.0005	0.0008	0.0006	0.0004
Mean Elong. Ult. Load	in.	0.171	0.257	0.323	0.164	0.175	0.181	0.171
Standard Deviation	in.	0.0134	0.0072	0.0182	0.0316	0.0297	0.0051	0.0070
Mean Elong. Rupt. Load	in.	0.37	0.38	0.53	0.35	0.31	0.33	0.34
Standard Deviation	in.	0.036	--	0.164	0.050	0.026	0.026	0.040

TORQUE TENSION CALIBRATION

Number of Specimens Tested		3	3	3	3	3	3	3
Mean Ultimate Load	kips	49.8	47.2	46.3	52.0	51.7	50.2	51.5
Standard Deviation	kips	0.28	0.77	0.58	0	0.58	0.29	1.32
% of Min. Ult. Load	%	93.6	88.7	87.0	97.7	97.2	94.4	95.7
Mean Rupture Load	kips	44.4	40.3	43.1	43.8	46.3	44.2	45.2
Standard Deviation	kips	1.10	2.52	1.10	1.94	1.16	1.76	2.25
Mean Elong. Proof Load	in.	0.014	0.026	0.033	0.015	0.015	0.017	0.018
Standard Deviation	in.	0.0009	0.0048	0.0059	0.0011	0.0028	0.0004	0.0006
Mean Elong. Ult. Load	in.	0.141	0.204	0.281	0.122	0.169	0.153	0.159
Standard Deviation	in.	0.0116	0.0119	0.0453	0.0116	0.0374	0.0161	0.0210
Mean Elong. Rupt. Load	in.	0.22	0.30	0.38	0.20	0.24	0.25	0.23
Standard Deviation	in.	0.023	0.051	0.052	0.011	0.022	0.019	0.017

+Grip length is defined as the distance between the inside faces of the bolt head and the nut

TABLE 3

HEAVY HEAD BOLTS WITH ROLLED THREADS

		H-Lot	E	E	8A	8A	8B	8B
Size (Nominal Diameter)	in.	7/8	7/8	7/8	7/8	7/8	7/8	7/8
Length Under Head	in.	9.5	5.5	5.5	5.25	5.25	5.5	5.5
Thread Length	in.	1.75	1.5	1.5	1.5	1.5	1.5	1.5
Grip Length +	in.	8.125	4.25	4.125	4.00	4.50	4.125	4.25
Thread Length in Grip	in.	0.375	0.25	0.125	0.25	0.75	0.125	0.25
Stress Area	sq.in.	0.462	0.462	0.462	0.462	0.462	0.462	0.462
Proof Load	kips	36.05	36.05	36.05	36.05	36.05	36.05	36.05
Minimum Ultimate Load	kips	53.2	53.2	53.2	53.2	53.2	53.2	53.2

DIRECT TENSION CALIBRATION

		H-Lot	E	E	8A	8A	8B	8B
Number of Specimens Tested		7	4	5	5	--	5	5
Mean Ultimate Load	kips	58.3	65.2	67.5	59.4	--	55.6	54.1
Standard Deviation	kips	1.29	1.04	1.01	1.12	--	1.00	1.60
% of Min. Ult. Load	%	109.6	122.6	126.9	111.7	--	104.5	101.7
Mean Rupture Load	kips	51.6	60.6	62.1	51.6	--	49.0	48.0
Standard Deviation	kips	2.72	1.68	1.43	1.70	--	0.81	1.41
Mean Elong. Proof Load	in.	0.018	0.011	0.010	0.010	--	0.010	0.011
Standard Deviation	in.	0.0002	0.0001	0.0004	0.0002	--	0.0003	0.0001
Mean Elong. Ult. Load	in.	0.1322	0.109	0.112	0.112	--	0.077	0.099
Standard Deviation	in.	0.048	0.0086	0.0236	0.0140	--	0.0021	0.0059
Mean Elong. Rupt. Load	in.	--	0.19	0.18	0.31	--	0.19	0.19
Standard Deviation	in.	--	--	--	--	--	--	--

TORQUE TENSION CALIBRATION

		H-Lot	E	E	8A	8A	8B	8B
Number of Specimens Tested		6	3	3	5	3	5	4
Mean Ultimate Load	kips	48.4	55.3	55.8	52.2	48.4	49.3	46.7
Standard Deviation	kips	1.69	0.72	2.86	1.90	1.35	1.69	0.33
% of Min. Ult. Load	%	91.0	103.9	104.9	98.1	91.0	92.7	87.8
Mean Rupture Load	kips	40.3	49.0	48.4	43.8	36.3	37.7	41.4
Standard Deviation	kips	2.61	5.38	7.74	3.28	1.53	3.10	1.66
Mean Elong. Proof Load	in.	0.019	0.012	0.011	0.010	0.010	0.012	0.013
Standard Deviation	in.	0.0005	0.0004	0.0012	0.0009	--	0.0005	0.0005
Mean Elong. Ult. Load	in.	0.066	0.055	0.059	0.055	0.083	0.052	0.055
Standard Deviation	in.	0.0144	0.0047	0.024	0.0222	0.0112	0.0063	0.0106
Mean Elong. Rupt. Load	in.	0.11	0.10	0.10	0.09	0.18	0.09	0.10
Standard Deviation	in.	0.029	0.085	--	0.038	0.029	0.014	0.008

+Grip length is defined as the distance between the inside faces of the bolt head and the nut

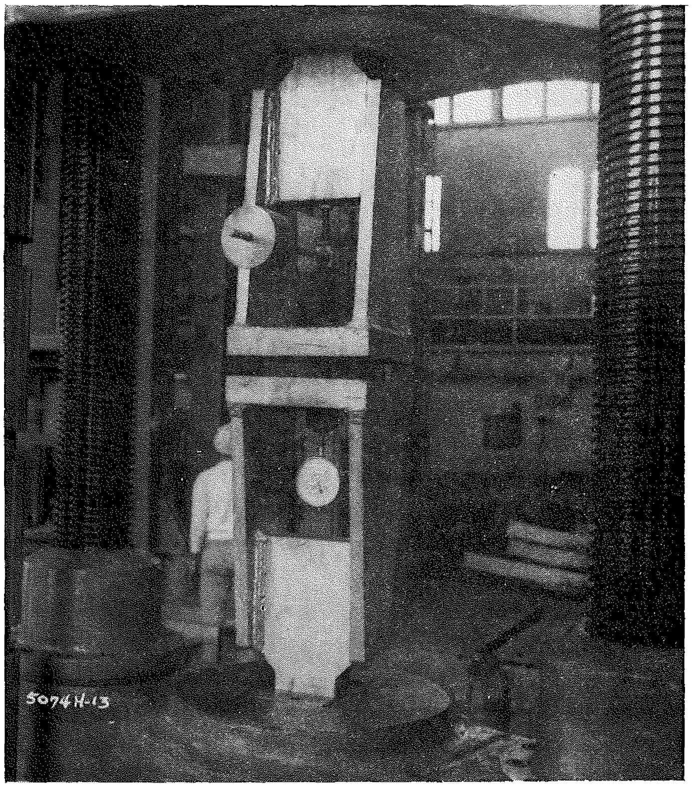

FIG. 1 DIRECT TENSION CALIBRATION SET-UP

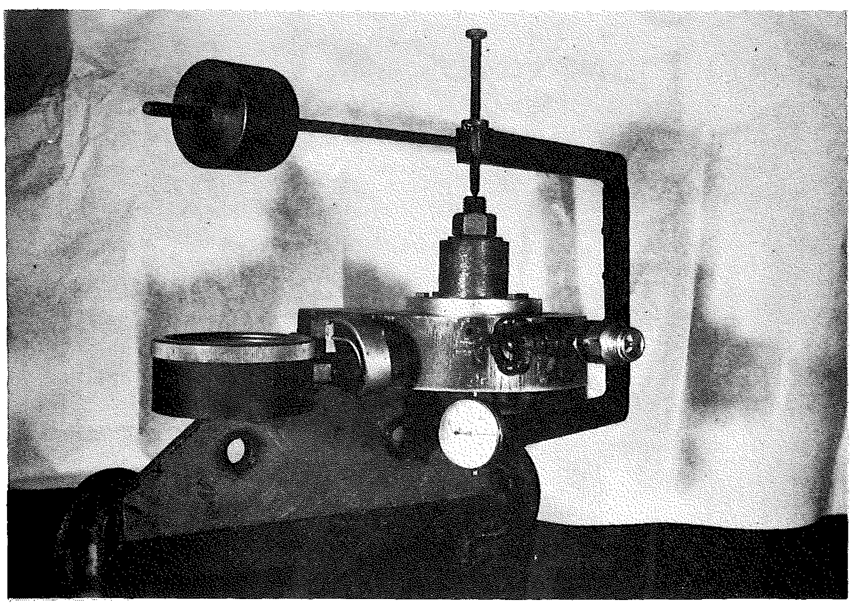

FIG. 2 TORQUED TENSION CALIBRATION SET-UP

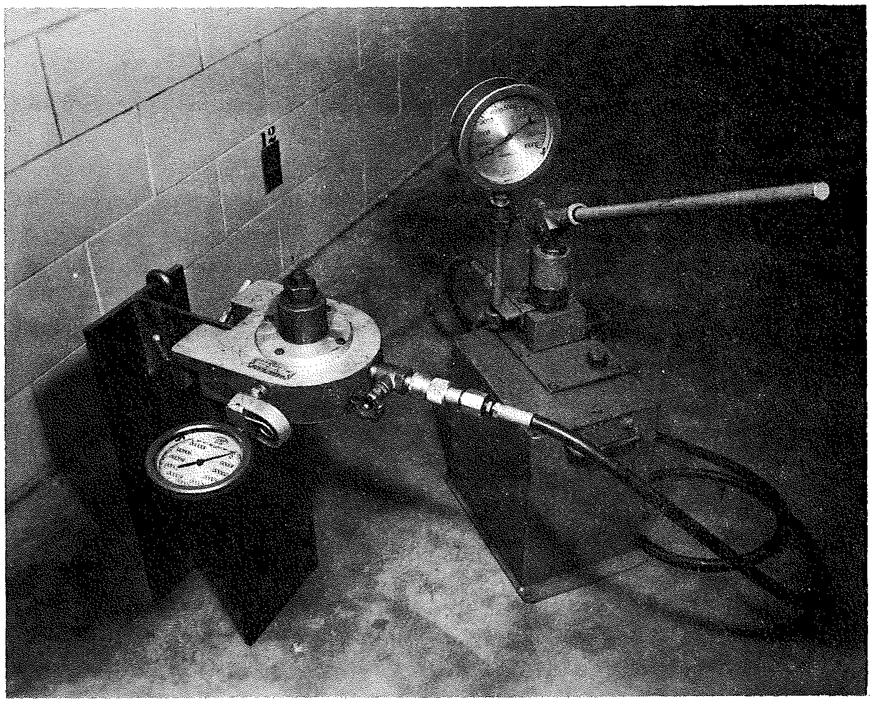

FIG.3 BOLT CALIBRATOR WITH HYDRAULIC PUMP

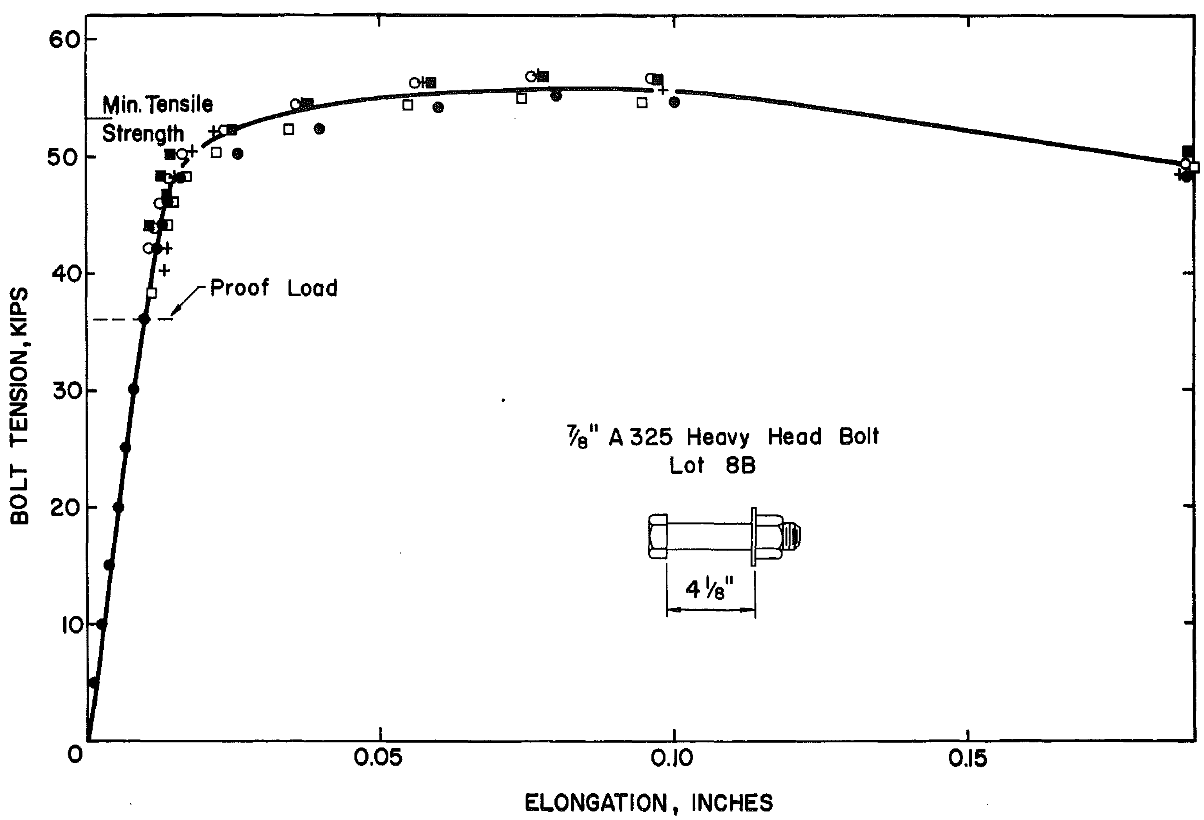

FIG. 4 LOAD-ELONGATION RELATIONSHIP, DIRECT TENSION

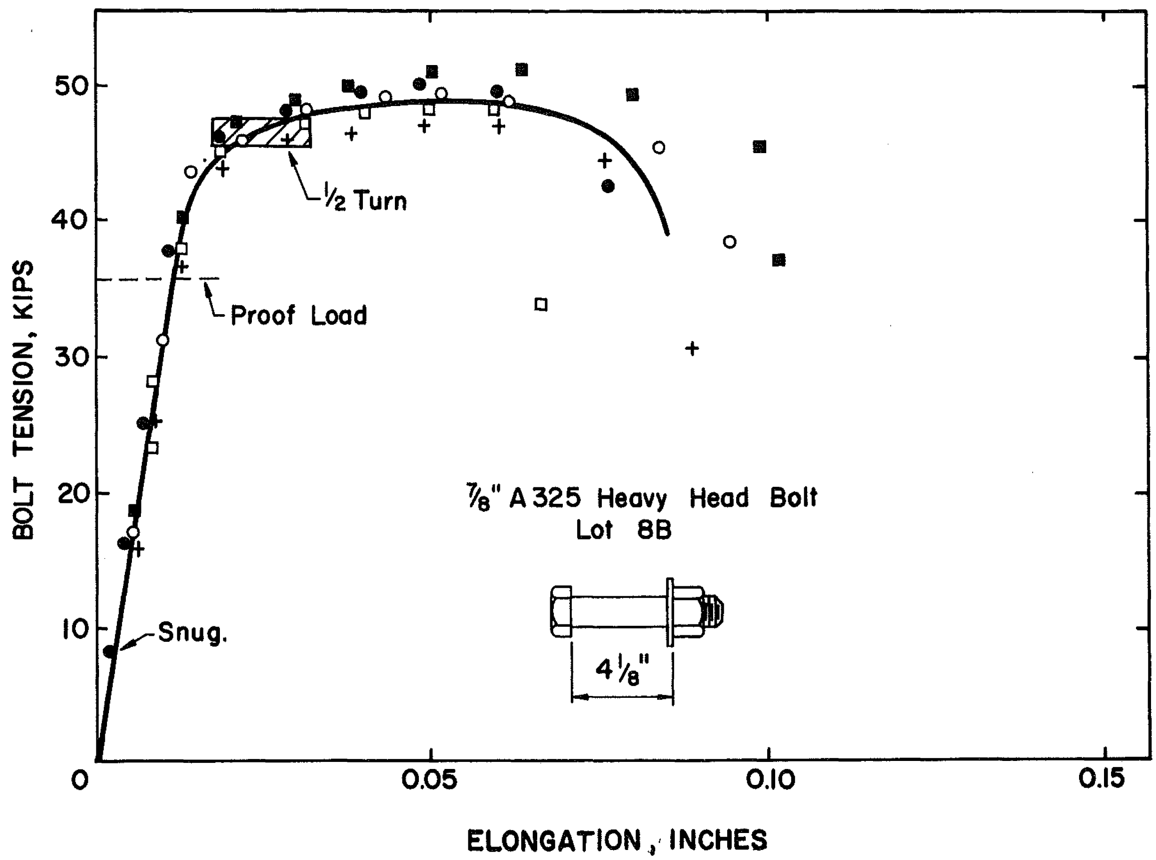

FIG. 5 LOAD ELONGATION RELATIONSHIP, TORQUED TENSION

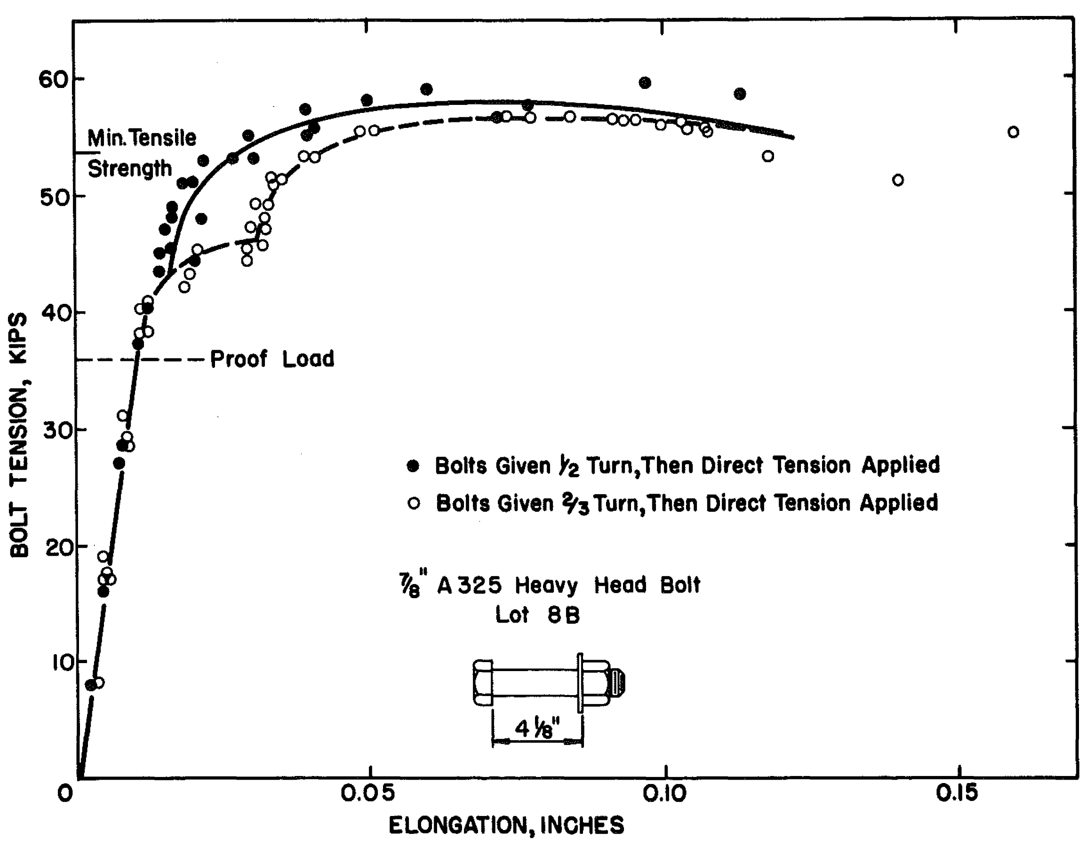

FIG. 6 RESERVED TENSILE STRENGTH OF TORQUED BOLTS

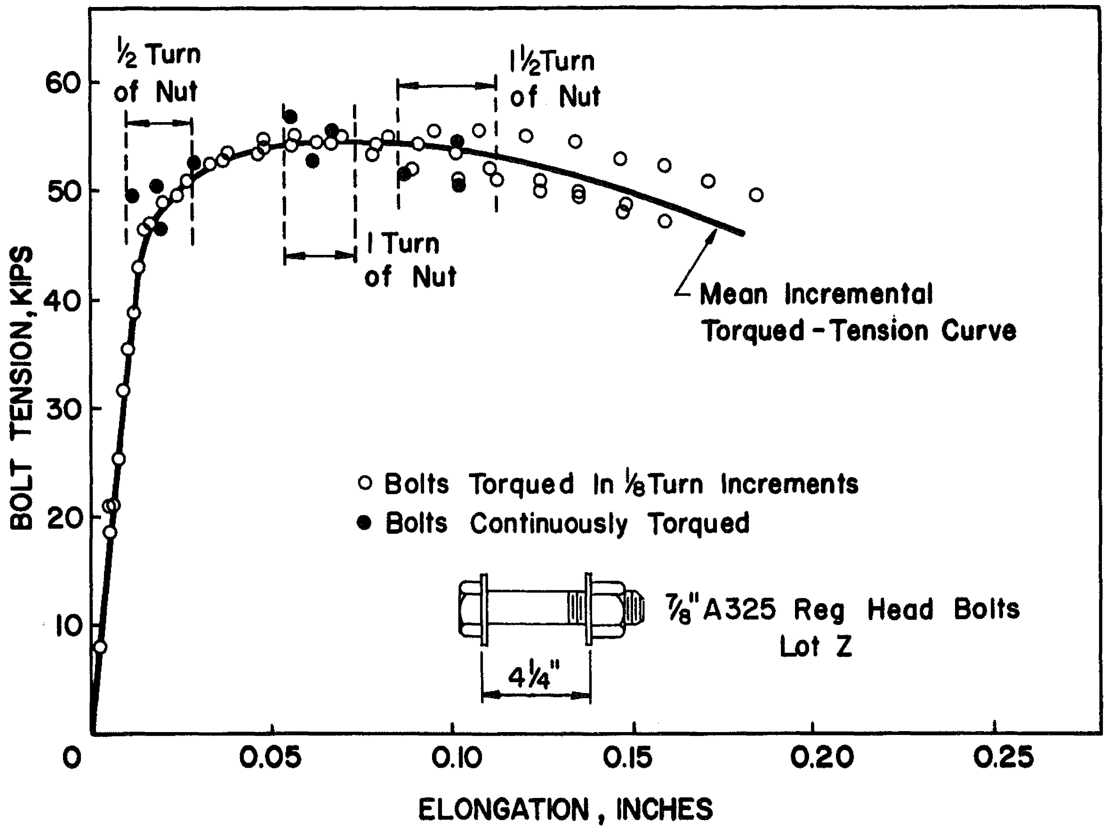

FIG. 7 COMPARISON OF CONTINUOUSLY AND INCREMENTALLY TORQUED BOLTS

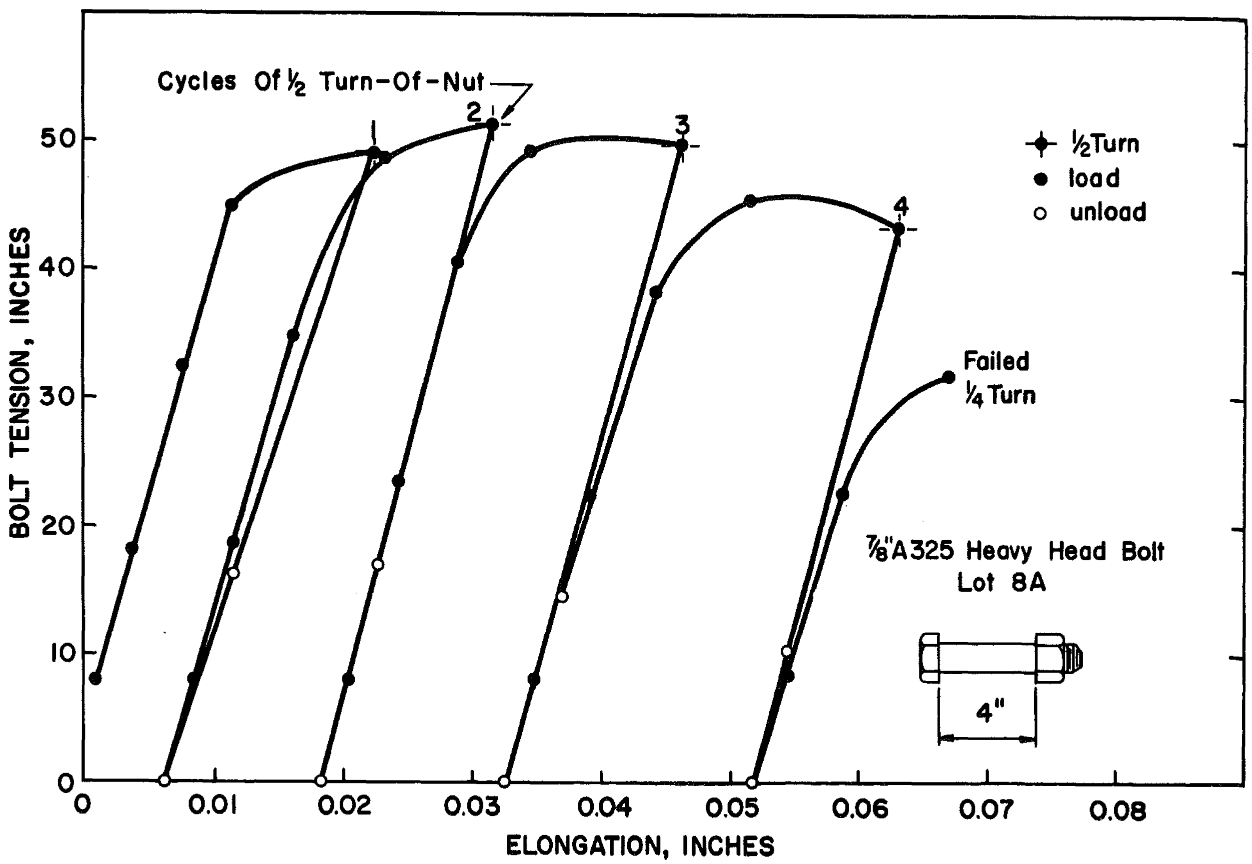

FIG. 8 REUSE OF HIGH STRENGTH BOLTS

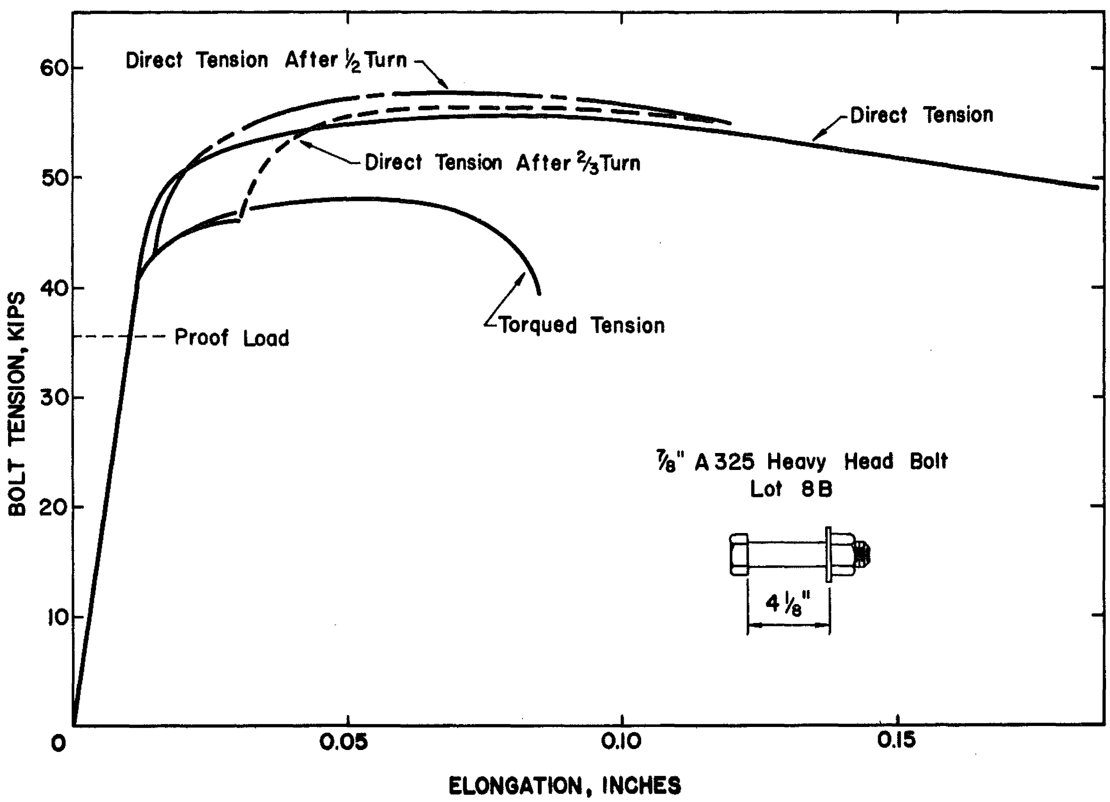

FIG. 9 COMPARISON OF LOAD ELONGATION RELATIONSHIPS

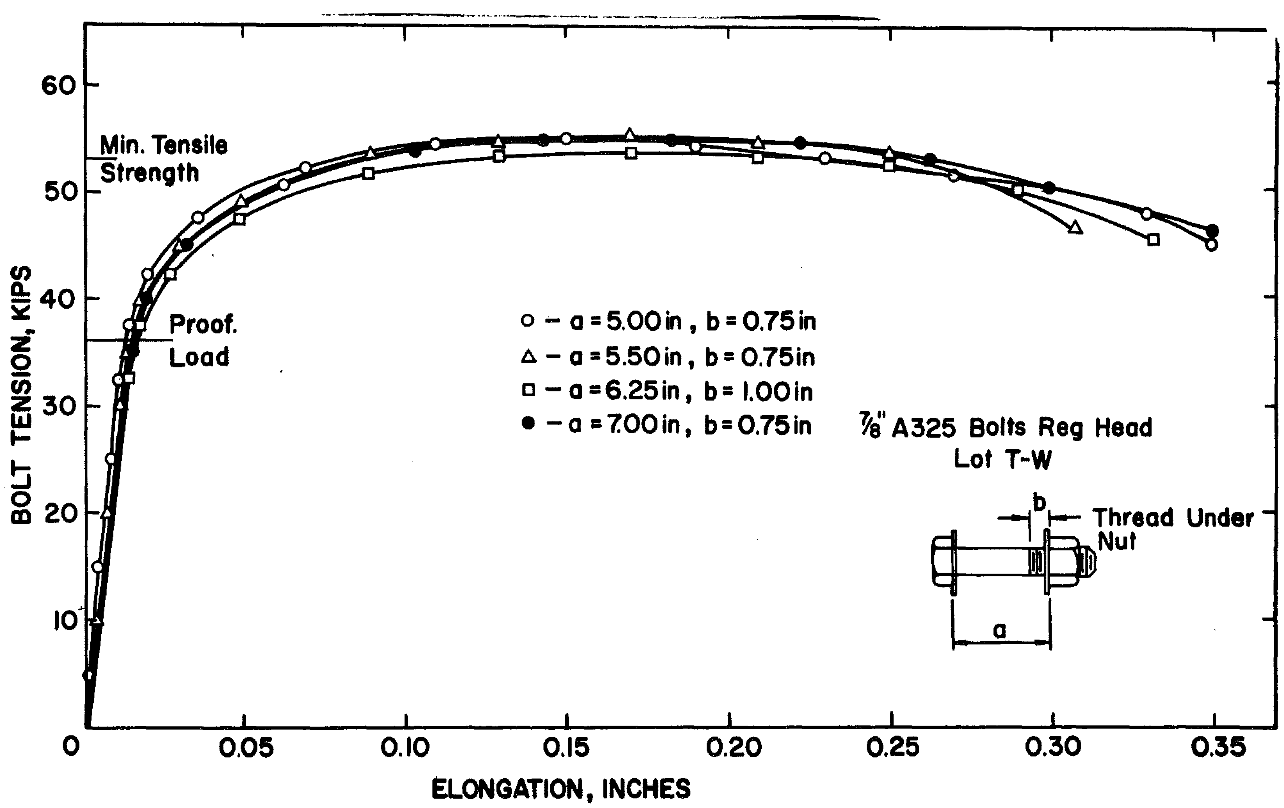

FIG. 10 EFFECT OF GRIP LENGTH, DIRECT TENSION

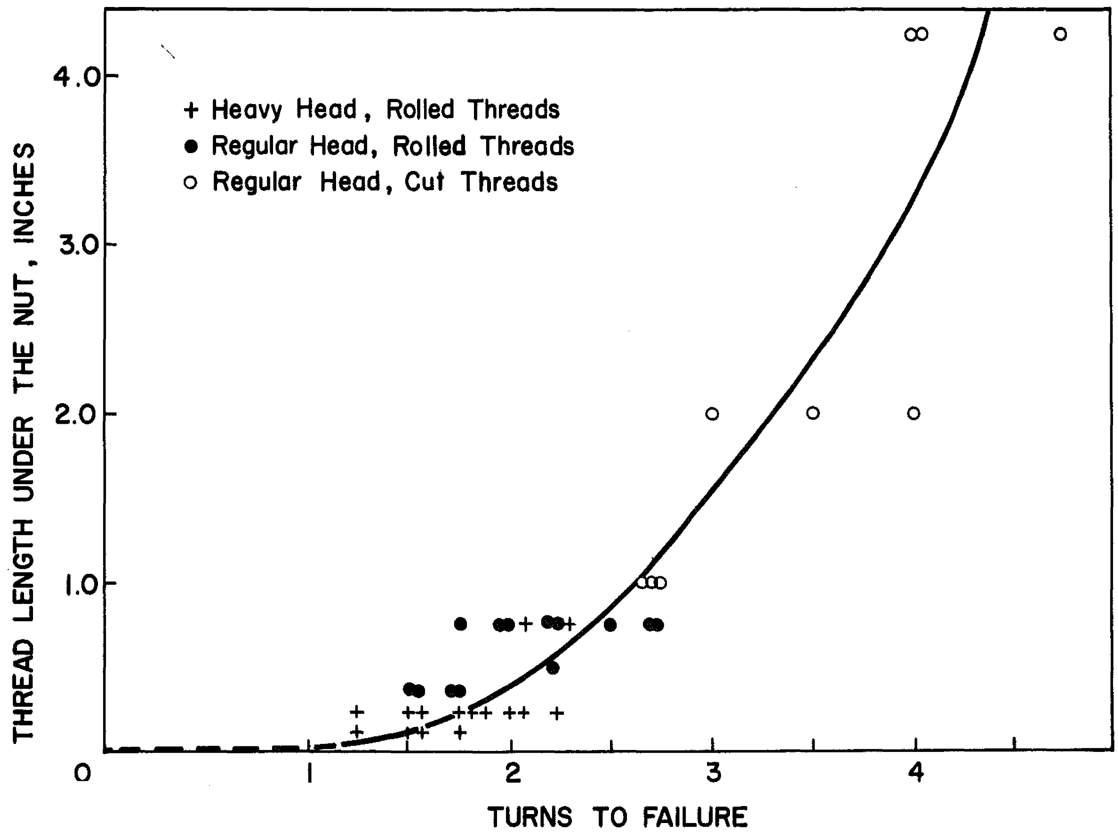

FIG. 11 EFFECT OF THREAD LENGTH ON ROTATION CAPACITY

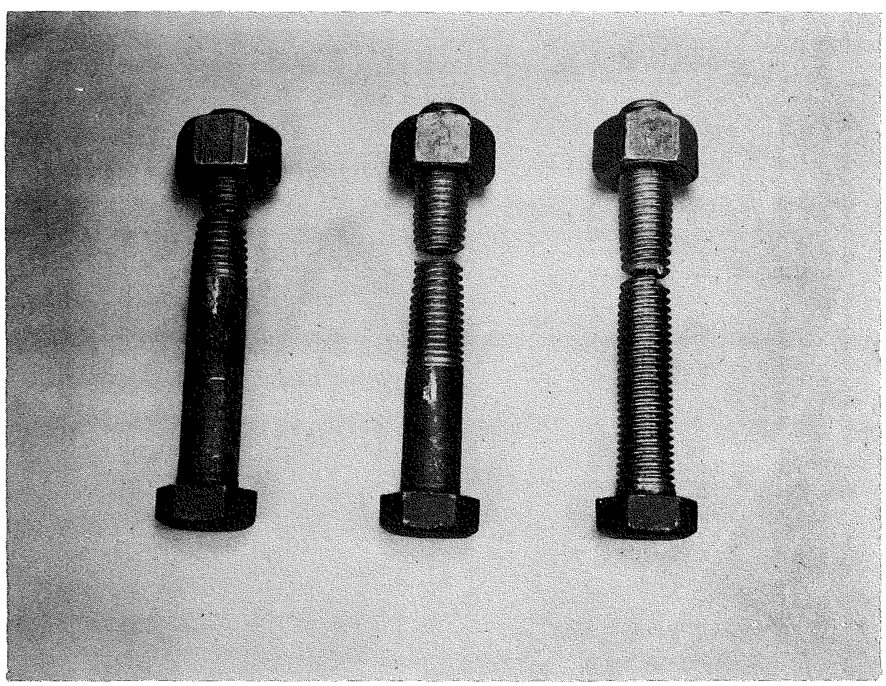

FIG. 12 INELASTIC DEFORMATION IN THREADED PORTION

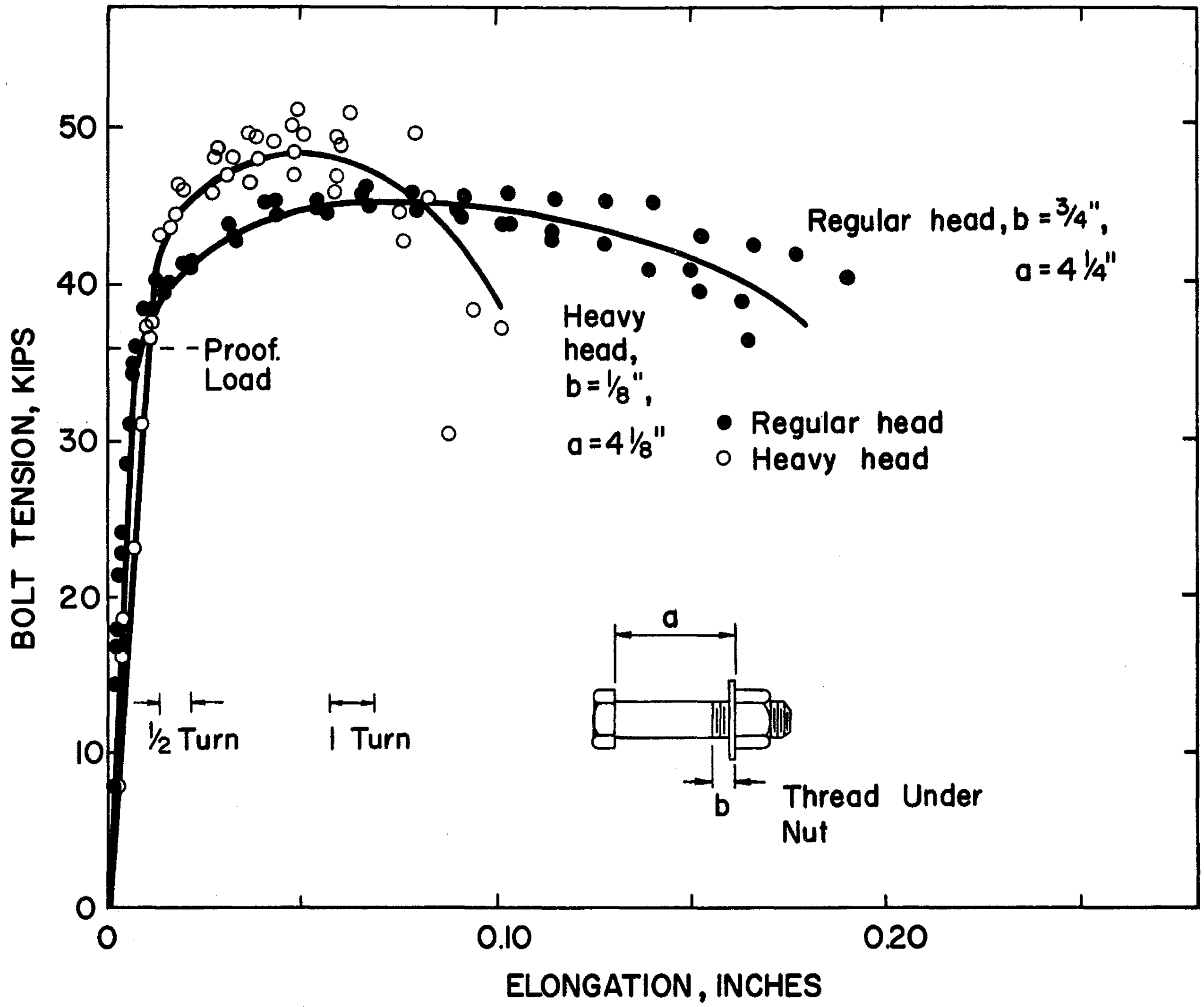

FIG. 13 COMPARISON OF REGULAR AND HEAVY HEAD A325 BOLTS