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Long Bolted Connections

CALIBRATION OF ALLOY STEEL BOLTS

by

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Fritz Engineering Laboratory Report No. 288.19A

LEHIGH UNIVERSITY
Bethlehem, Pennsylvania

Department of Civil Engineering
Fritz Engineering Laboratory

July 26, 1965

288.1

Members of Committee 10 - RCRBSJ, T. W. Spilman, Chairman
"Static Strength of Bolted High Strength Steel Joints"

Messrs: L. S. Beedle, R. Belford, J. Giliberto, F. E. Graves, N. G. Hansen, R. M. Hansen, T. R. Higgins, B. F. Kotalik, W. H. Munse, E. J. Ruble, J. L. Rumpf, T. W. Spilman, G. S. Vincent

Gentlemen:

As a result of discussion at a meeting of Committee 15, RCRBSJ, on July 19, 1965, the following clarifying remarks are in order with regard to Fritz Laboratory Report No. 288.19A, entitled "Calibration of Alloy Steel Bolts". Also, as a result of these remarks the attached addendum to Report 288.19A has been prepared for your consideration. A majority of the members of Committee 10 were present at the meeting and participated in the discussion.

1. It was recognized that about 20% of the bolts in this study were purposely ordered to ASTM minimum and that only 2% of these had torqued tension strengths that were less than proof load. Also, those bolts having torqued tension strengths less than proof load had more exposed thread under the nut than the A490 bolt would have. Because of these factors we consider our recommendation regarding the necessity to increase the specified ultimate load as overly conservative and have revised the manuscript to reflect this.

2. The point was raised in Report 288.19A that the flexibility of the calibrator may make it comparable to some field installations in which conditions are not ideal. After discussion of this point it was generally agreed that the calibrator is not indicative of properly snugged joints, at least the great majority of them. Also, it should be noted that even in the calibrating device the mean clamping force is above proof load. We have retained mention of the

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question on page 21 so that some guidance is given should a special situation arise. However, we are in agreement that the A490 bolt should not be penalized because this condition might exist in a few joints.

3. The point was also brought out that although some bolts in soft joints may have less tension than required, this would not significantly affect the joint behavior. A margin against slip is provided in the factor of safety and numerous tests have indicated that some minor slip can be tolerated.

We would be pleased to receive any comments or suggestions you might have on these remarks and the addendum to Report 288.19A.

Sincerely yours,

John W. Fisher

John W. Fisher
Research Assistant Professor

JWF/va
Encl:
cc: Messrs: C. D. Jensen, E. G. Wiles, R. C. Updegraff, J. L. Stinson, J. W. Burdell, Jr., Members, RCRBSJ

ADDENDUM

tensile strength, it is possible that the ultimate load in torqued tension could be below proof load for minimum strength bolts. (As shown in Table 3, the bolts used in these tests had mean tensile strengths ranging from 102% to 113% of ASTM minimum, the average value being 108.3%).

Figure 9 gives some indication of the possibility of A490 and A354 BD bolts falling below specified proof load. A plot of the average non-dimensional load vs. elongation of bolts in direct tension and bolts in torqued tension is shown as a frame of reference. These are composite results obtained by considering all of the results contained in this report (using only as-received threads in the case of the torqued tension curve).

The distribution of direct tensile strength is designated in Fig. 9 as "a". This shows that only 2.6% of the sample fell below the minimum specified tensile load. Distribution "b" in Fig. 9 shows the frequency distribution of the ultimate torqued tension load for the bolts tested. 1.5% of the sample had a torqued tension strength that

Revision starts

was less than proof load. Only bolts that were purposely ordered to minimum strength level had torqued tension strengths that were near or less than proof load. It has been suggested that most production bolts would be about 10% stronger than the ASTM minimum, and in this case the torqued tension strength would exceed proof load. Also, an examination of Tables 4 and 5 shows clearly that bolts with short thread under the nut had a substantial increase in direct and torqued tension strength.

(The bolts which failed to meet the proof load all had more thread under the nut.) Hence, even minimum strength A490 bolts should have torqued tension strengths which exceed proof load because of their short lengths of thread under the nut.

Distributions "c" and "d" in Fig. 9 show the frequency distribution of bolt tension after tightening the bolt by rotating the nut the specified amount. Distribution "c" shows the results of 165 bolts installed in steel plate (test joints(17) and special jigs). Distribution "d" shows similar results for 106 bolts installed in the hydraulic calibrator. (In each case, as-received threads were used.) These distributions show that at specified nut rotation only 3.2% of the sample installed in steel plate and about 37% of the hydraulic calibrator sample fell below proof load.

Bolts installed in the test joints and special jigs are representative of the installation conditions for well compacted joints. The flexibility of the calibrator may make it comparable to a few field installations in which conditions are not ideal. In such cases, because of the possibility of pretension less than specified minimum proof load, a decrease in allowable shear stress in friction-type connections is the only safe alternative. An increase in tensile strength would not affect the amount of induced elongation for the specified nut rotation and an increase in specified rotation would decrease the rotational factor of safety against twisting off.

Revision ends

The effects of grip length on the load-elongation relationship of the alloy steel bolt are illustrated in Fig. 10 for 7/8-in. A490 bolts. Both lots had the same thread length under nut. The relationship for the shorter bolt, shown by the solid line, has a steeper elastic slope than for the longer bolt; and although the elongations at ½ turn-of-nut

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pg. 30: Delete conclusion 13 from the text.

CALIBRATION OF ALLOY STEEL BOLTS

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Richard J. Christopher

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This work was carried out as part of the Large Bolted Connections 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
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Bethlehem, Pennsylvania

July 1965

Fritz Engineering Laboratory Report No. 288.19A

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S Y N O P S I S

This report is based on results of tests of a large sample of A354 and A490 bolts studied to determine their tensile behavior when used as structural fasteners. Variables included bolt diameter, grip length, thread length under nut, and thread lubrication. Bolts were tested under various loadings to determine their behavior under conditions often encountered in the field. When correctly used, these bolts are satisfactory structural fasteners.

1. INTRODUCTION

1.1 PURPOSE

The objective of this study is to determine the performance of the alloy steel structural bolt when subjected to various conditions of installation and load. A knowledge of this behavior is required for the intelligent use of this bolt as a structural fastener.

Knowledge of the tensile behavior of a bolt is important. First of all, this behavior affects installation practices and methods of inspection. Secondly, in a joint designed to resist forces with bolt tension, information is needed to predict the deformation and load capacities of the connection. Finally, in a friction-type joint the available frictional resistance before the joint slips into bearing is directly controlled by the tensile forces in the bolts. For these reasons, relationships must be established to predict the behavior of a bolt loaded in tension by either a direct axial force or by a combination of direct axial force and torque.

In addition to the basic tensile behavior, several other problems deserve attention. These are:

(1) The response of alloy steel bolts installed by torquing to subsequent application of direct tension

(2) The effect of reinstallation

(3) The possible differences between tests performed in a hydraulic load cell and field behavior of the bolts as installed in a joint

(4) The differences between incremental torquing to a given nut rotation (laboratory procedure) and continuous torquing (field procedure)

(5) The effect of thread lubrication.

The various methods of relating internal bolt tension to a readily observed quantity such as torque, elongation, strain in the shank of the bolt, load cell output, and turn-of-nut are discussed in Ref. 1, which also presents a list of studies of A325 bolts. Several recent investigations of alloy steel bolts were reported in Refs. 2 and 3. Preliminary results of the present study were first reported in Refs. 4 and 5.

1.2 TEST PROGRAM

The test program included the study of the tensile behavior of eight lots of bolts conforming to ASTM A354-58T, Grades BC and BD,[6] and eight lots conforming to the A490 specification[7] for quenched and tempered alloy steel structural bolts. The A490 specification calls for the heavy head and short thread length of the A325 specification[8] together with chemical and physical properties nearly identical to the A354 grade BD bolt. Bolt lots AD, BD, CD, and DD were made to conform to the A490 specification by re-heat treating bolts manufactured to AISI specification 4140.

Both 7/8 and 1-in. heavy and regular semi-finished hexagon head bolts were tested. ASTM A194[9] grade 2H nuts with heavy semi-finished heads were used with all bolts tested and hardened washers were used under all nuts. All reference to bolt head and nut size is that defined in the American Standards Association specification B18.2.[10]

Table 1 gives a complete description of the test specimens, including such variables as length under head (L), grip length (g), thread length under nut (t), diameter, head size, and type of thread. Each lot of bolts is identified by two letters followed by a series of numbers and letters. The first number following the double letters indicates the bolt diameter in eighths of an inch. The next number or numbers indicates the length of thread under the nut in sixteenths of an inch. Finally, the letter S or L at the end of the designation differentiates between short (approx. 4-in.) and long (approx. 8-in.) grip lengths. For example, the designation AC-7-9S indicates a 7/8-in. diameter lot AC bolt with 9/16-in. thread under the nut and a short grip length.

Since these tests were initiated to aid in the development of the A490 bolt and since the A354 bolt was not yet in general use as a structural fastener, all of the bolts used for this study were specially manufactured and therefore exhibited a greater variation in properties, both geometric and structural, than would ordinarily be expected. Special attention was given to the resulting problems, which included sub-standard thread fit for some lots, a wide scatter of individual test results, and, on the A354BC grade bolts, a complete lack of the residue oil which is normally present.

Although wax has been used as a lubricant for some time in certain applications such as on fasteners used in the automotive and aircraft industries, its effect on the behavior of structural fasteners was not well established. It was considered desirable to determine whether or not some important advantages might be gained by its use. In order to complete the program, the behavior of bolts lubricated with a heavy, multi-purpose type grease was also investigated. The properties of the bolts under torqued tension and under repeated torquing could then be compared for the three conditions of lubrication; residue oil, heavy multi-purpose type grease, and wax.

The overall test program was planned to investigate the previously discussed major and secondary types of tensile behavior of these bolts. Hardness tests were performed and tensile tests made on 0.505-in. diameter specimens turned from full-size bolts in order to establish trends based on the material properties as specified in the ASTM Standards.

2. TEST PREPARATION AND PROCEDURE

2.1 PREPARATION OF BOLTS

Before testing both ends of each bolt were stamped with a lot designation and number. The bolts were then drilled and countersunk at each end to accommodate the C-frame extensometer which was used to measure changes in length due to tightening.

Each bolt was checked for thread fit with the NC2A "Go" and "No-Go" ring gages, and each nut was similarly checked with the NC2B plug gages. Bolts and nuts with improper thread fit were rejected for use in the test program.

2.2 TESTING EQUIPMENT

Bolt coupons were tested in a 60 kip universal testing machine. Threaded tension grips were used to hold the coupons and elongations were measured with a Peters extensometer or an autographic recorder.

A 300 kip universal testing machine equipped with special tension grips to hold the bolt under head and nut was used for the direct tension tests of full-size bolts.

Two different hydraulic bolt calibrators were used to measure bolt tension during the torqued tension tests. One with a capacity of 100 kips was used for most tests of 7/8-in. bolts.(11) It was coupled to an oil pump to test the bolts in combined torqued-then-direct tension. The other, with a tensile capacity of 220 kips, was used for all torqued tension tests of 1-in. bolts.

All bolt elongations were measured with a C-frame extensometer consisting of a rigid, adjustable steel frame and an Ames dial with divisions of 0.0001-in. A counterweight was connected to the upper arm of the frame so that it balanced in the measuring position.

A large capacity pneumatic impact wrench running on a line pressure of approximately 130 psi at the wrench was used for all torqued tension tests. The wrench capacity was adequate for all bolts tested.

Additional details of the testing equipment are given in Ref. 1.

2.3 COUPON AND HARDNESS TESTING PROCEDURES

Coupon and hardness tests were conducted according to the applicable testing procedure specified in ASTM Designation A370.[12] Coupons of 0.505-in. in diameter were prepared and tested at an indicated strain rate of approximately 0.02-in. per minute. A complete stress-strain curve was obtained for each coupon. Particular emphasis was placed on ultimate tensile strength, final elongation, and final reduction in area. Either an autographic recorder or a Peters gage was used to measure elongation in the elastic and initial plastic range, and a steel scale and dividers were used for the remainder of the test. The final cross-sectional area at the fracture was determined by using a micrometer to measure two mutually perpendicular diameters and using the mean value to calculate the equivalent circular area.

Hardness tests were conducted on the sides of the bolt head and on a transverse section one bolt diameter from the threaded end. A belt grinder equipped with cooling water was used to remove all scale from the areas to be tested and to obtain a smoothly polished surface. Standard Brinell and Rockwell C hardness tests were then conducted. Two trials were made on each bolt for each type of hardness test and at least two bolts from each lot were tested.

2.4 DIRECT TENSION TESTING PROCEDURE

Each bolt was installed in the tension grips of the hydraulic testing machine with the proper thread length under the nut. The initial bolt length was then measured with the C-frame extensometer with no load on the bolt. With the extensometer still in place, the bolt was loaded to its specified proof load. The load was then removed and the length was again measured to determine whether or not permanent set had occurred. If the permanent set exceeded 0.0005-in., the bolt was rejected as not meeting the specification. Of the 84 bolts tested in direct tension only three were rejected on this basis. Two of these were later found to have microscopic cracks through their shanks at the base of the head so that their effective area at that point was about one half of the shank area.

After the bolt was checked in this manner it was again loaded, this time to failure. Load was applied at a rate of approximately 0.01-in. total elongation per minute. Loads and elongations were measured at 10 kip intervals in the elastic range and at 0.01-in. increments in the inelastic range until ultimate load was reached. Then, after one or two more readings, the extensometer was removed and the bolt was allowed to fail at the same rate of elongation. During the inelastic range of the test, the machine was stopped one or more times to determine the static load level. This was consistently found to be about one kip below that at testing speed. The same reduction was noted in Ref. 1 for tests of A325 bolts.

After failure, the bolt was fitted together as well as possible and the final measurement of elongation was made with the C-frame extensometer or with a steel scale with .01-in. divisions.

Only bolts with threads in the as-received condition were tested in direct tension.

2.5 TORQUED TENSION TESTING PROCEDURE

After the initial length was measured, the bolt was installed in the bolt calibrator with the proper thread length under the nut. This adjustment was obtained by using heavy packing washers to vary the gripped length. These washers had milled surfaces which provided a tight fit between adjacent washers and the bearing plate of the bolt calibrator.

The bolt was first tightened with a hand wrench to a "snug" load of 8 kips (10 kips for the LI, AB, and JJ lots). The nut was then turned with the impact wrench in 45° (1/8 turn) increments until failure. Tightening was stopped at each increment and load and elongation readings were taken. After failure the final elongation was measured, in most cases with a steel scale, and type of failure was recorded. This general procedure was followed for all tests in which wrench tightening was used.

Bolts with threads in the three conditions of lubrication were tested in torqued tension. A354 BC bolts were received completely dry and it was necessary to apply a light, water soluble oil in order to simulate the residue oil. For the grease-lubricated thread tests a heavy, multi-purpose type grease was applied to both the nut and the bolt. Bolts to be tested in the waxed condition were prepared by a bolt and nut manufacturer as follows. The elements were first cleaned in solvent, then emersed in wax, and finally spun to remove the excess. The wax used was a commercial preparation composed of vegetable waxes, oxidized petroleum waxes, metal-organic soaps, heavy molecular weight amine fatty acid, and heavy-weight polybutene, all dissolved in stoddard solvent.[13] Half of the specimens had the wax applied to the bolt and the other half had the wax applied to the nut. Waxed bolts were then used with unwaxed nuts and waxed nuts used with unwaxed bolts.

2.6 TESTING PROCEDURE - SPECIAL TESTS

The tests of bolts loaded in direct tension after being preloaded by a given nut rotation with an impact wrench were all conducted in the smaller bolt calibrator. The bolts were first tightened in 1/8 turn increments until 5/8 turn-of-nut was reached. The oil pump was then brought up to a pressure equivalent to that in the load cell for the bolt tension indicated. The valve between load cell and pump was opened and the load was allowed to stabilize. The resulting change in load was never more than ± 1 kip. The extensometer was then placed on the bolt and the bolt was loaded directly with the oil pump without further nut rotation. Loads and elongations were measured at small intervals until several readings had been taken beyond the ultimate load. Finally, the extensometer was removed and pumping continued until bolt failure. Final elongation was measured with the extensometer and the type of failure was recorded.

The testing procedure for repeated wrench installation of bolts was the same as that of the regular torqued tension tests except that after a specified nut rotation, the nut was loosened incrementally until all load was removed. This procedure was repeated until bolt failure. Final load, elongation, and number of cycles to failure were then recorded. These tests were conducted to determine the effects of reinstallation of alloy steel bolts in the field. Bolts with threads in two conditions of lubrication, residue oil and wax, were used for these tests.

Several bolts were installed in steel plates and bolt load was not recorded during these tests. The bolts were installed in the steel plate to the elongation corresponding to "snug" load of the regular torqued tension tests. Then they were loaded to failure in 45° increments. Elongation was measured at each increment. Lot LI bolts were tested in a 4-in. square block of A440 steel with a 15/16-in. hole through it. Lot ED bolts were tested in four 1-in. plies of A440 steel having the same overall dimensions as above. The remaining lots were tested in the bolt calibrators with all oil removed and the cylinder bearing against the casing of the cell. Packing washers were used to provide the proper grip. The last method, by far the easiest of the three, gave results consistent with those of the first two methods. Only bolts with threads in the as-received condition were used.

A number of bolts were continuously torqued to a specified nut rotation for comparison with bolts torqued by incremental nut rotation. They were first snugged with a hand wrench and then tightened with the impact wrench in the bolt calibrator. When the specified nut rotation was reached, the load and elongation were recorded.

3. RESULTS AND ANALYSIS

3.1 COUPON AND HARDNESS TESTS

The results of all bolt coupon tests are listed in Table 2 and compared to minimum values specified by ASTM. All values for strength and ductility exceeded specified minimum values except the tensile strength for lot BD which was 98% of the specified value. The elongations listed are for a gage length of 1.9-in. rather than the 2.0-in. specified by ASTM. However, these values exceed the specified values by a large margin except for the BD lot. Figure 1 shows a typical stress-strain curve for a coupon cut from lot KK A490 bolts.

Table 3 lists the results of the Brinnell and Rockwell C hardness tests for each bolt lot. Values obtained using the Standard procedure (testing surface on bolt head) were all within the limits as set out by the applicable ASTM specification. The Arbitration method (testing surface on a transverse section one diameter from the threaded end) gave hardness values generally higher than those obtained by the Standard procedure. In some cases, these values exceeded the ASTM allowables. Also shown is the tensile strength for each lot of bolts.

3.2 DIRECT TENSION TESTS

Figure 2 shows typical results of direct tension tests of A325, A354 BC and A490 bolts. The curves shown are for bolts having nearly equal grip lengths and thread lengths under the nut. It is obvious that increased bolt strength is accompanied by a decreased deformation capacity. The bolts were still elastic at proof load. After reaching ultimate load, the bolts had less capacity for further deformation than did the coupons because of restraint caused by the shank and nut and the relatively short gage length of the highly-stressed threaded portion.

A number of direct tension tests were conducted with six threads under the nut as specified by ASTM A370. The ultimate tensile strength for each of these lots is reported in Table 3 and compared to the corresponding ASTM minimum specified value. Bolt strength varied from 102 to 113% of that specified by ASTM. If these percentages are compared lot by lot with those from the coupon tests recorded in Table 2, it will be noticed that there is usually close agreement between the two. The largest discrepancies occur for the 1-in. bolts (lots BC, DC, BD, and FD) where the coupon strengths are always the lower of the two values. For example, the BD lot coupon tests indicated that the mean tensile strength was 98% of the required tensile strength, while the mean ultimate load of the bolts tested was 110% of that specified. If the increase of bolt strength over coupon strength were a constant ratio, it could be ascribed to differences in test methods or to small inaccuracies in the concept of stress area. However, since the effect is much more pronounced with the larger diameter bolts, it is likely that this is the result of a decreasing effect of heat treatment near the center of the larger bolt.

Table 4 contains the results for all bolts tested in direct tension. The results of these direct tension tests indicate that bolts with short lengths of thread under the nut have significantly higher tensile strengths and lower failure elongations than bolts from the same lot tested with more thread under the nut. This higher strength is partially the result of a small decrease in thread depth near the thread runout which results in a larger cross sectional area. The strength may also be higher becuase failure is forced to occur over a relatively short length of thread. Bolts with longer thread lengths under the nut normally failed on a diagonal plane in both the direct and torqued tension tests as indicated in Fig. 3a, while the failure planes were less inclined when the thread length under the nut was shorter as shown in Fig. 3b. This change in the plane of failure, together with the larger restraint to lateral contraction caused by the proximity of the nut and the bolt shank to the zone of maximum stress, resulted in increased tensile strength. Because of the short length of the highly-stressed threaded portion, elongation capacity is reduced for short thread lengths under the nut. Two bolts with short threads failed by thread stripping but only after having reached an ultimate load well above the specified minimum tensile strength.

The theoretical elastic behavior of the threaded fastener can be computed readily if some simplifying assumptions are made. The threaded portion can be assumed to be a uniform shaft with a cross sectional area equal to the stress area (as defined by ASTM A370). It can also be assumed that the full tensile load acts between the inner face of the bolt head and the mid-point of the nut. Using these assumptions, computed elongations differed by a maximum value of 9% and an average value (for 24 tests) of 2½% as compared to the elongations measured using the C-frame extensometer.

3.3 TORQUED TENSION TESTS

Three series of torqued tension tests were conducted. These tests were the same in all respects except for the mode of thread lubrication. The three conditions of lubrication were "as received" (threads lubricated only with the residue shipping oil), threads lubricated with heavy, multi-purpose type grease, and threads lubricated with wax. Details of these lubricants were given earlier.

Tables 5 and 6 show the results of the torqued tension tests for bolts in the three conditions of lubrication. These tables list the mean values of load at ½ turn-of-nut from snug, 5/8 turn-of-nut from snug, the ultimate torqued tension load, the rupture load, the ultimate torqued tension load as a percentage of the ultimate direct tension load for the same lot, the elongation at ½ turn-of-nut, and the number of nut revolutions to failure. The 5/8 turn values are reported because they are the closest available to the 2/3 turn specified for bolts having lengths under head greater than eight inches or eight bolt diameters, whichever is smaller.(14)

Figure 4 shows the typical behavior of A325, A354 BC, and A354 BD (or A490) bolts in torqued tension. Each lot shown was tested with 3/4-in. thread under the nut and a grip length of either 4¼ or

$4\frac{1}{2}$-in. As in the direct tension tests, the higher-strength bolts show smaller elongations to failure under torqued tension. The higher-strength bolts also reach ultimate load at a smaller elongation and the load then drops off more quickly than with A325 bolts. This was also true for the direct tension relationships shown in Fig. 2.

Figure 5 allows a comparison of loading methods, direct tension vs. torqued tension, and method of thread lubrication. The ultimate strength in direct tension is substantially greater than that in torqued tension. Many investigators have observed this increase in A325, A354, and A490 bolts.[(1)(2)(3)]

It is clear from Figure 5, and from the test results as a whole, that the type of thread lubrication has only a slight effect on the torqued tension behavior. The most significant effect of the waxing was in the type of bolt failure. (It should be noted that whether the waxed element was the nut or the bolt, substantially the same results were obtained for a given bolt lot.) Practically all failure of bolts lubricated with residue-oil or greased threads were of the "torqued" type (that is, the bolt was sheared off under combined shear and tension.) Of the 70 torqued tension tests performed using waxed elements, 44 specimens failed by stripping of the threads.

The torqued failure, which has been explained on the basis of the principal stress theory[(15)(16)] and the principal strain theory[(16)] is such that at some point the bolt and the nut essentially "lock together" and the bolt fails through the shank under the combination of high shear and direct tension. The lubrication provided by the wax was in most cases sufficient to prevent this "locking" action. As the nut continued to turn with reference to the bolt, high bearing pressure and galling of the nut surface caused the base of the nut to spread. Also, some necking of the bolt occurred near the nut face. The resulting increase in load on the threads remaining in contact caused the stripping failure. This spreading of the base of the nut was apparent in almost all tests using waxed elements. In the cases where the thread length under the nut was small, the stripping failure occurred as the nut rode up onto the thread run-out of the bolt.

An additional effect of the use of wax as a lubricant was that it increased the number of turns to failure for a given bolt lot. This is shown in Fig. 6 for a typical lot of bolts. An average increase of ¼ turn-of-the-nut was obtained for all lots tested.

It has been found that the mean elongation at ½ turn is fairly constant for most of the bolts tested. For the higher-strength, long-grip bolt this elongation may be entirely due to elastic deformations, whereas for the lower-strength bolt both elastic and inelastic deformations may be included. For example, Fig. 7 compares the torqued tension behavior of A325 bolts with a grip length of 8-1/8-in. with that of A490 bolts with a grip length of 8-11/16-in. The elongation and load at ½ turn-of-nut are nearly identical for the two bolt lots. The ½ turn is well into the inelastic range and above proof load for the A325 bolt; however, it is in the elastic range and below proof load for the A490 bolt. In general, as bolt strength and grip length increases, so does the elongation to the elastic limit or proof load.

The compressive deformation of the material being gripped also increases with higher bolt tension. These effects combine to require larger nut rotations to induce proof load in the high-strength bolts, especially those with long grip lengths.

A bar graph of loads at ½ turn, 5/8 turn, and ultimate for A354 and A490 bolts with threads either in the as-received or waxed condition is shown in Fig. 8. The load scale is non-dimensional so that 7/8 and 1-in. diameter bolts may be compared. It can be noted that lubrication had little effect on the results. The load at ½ turn-of-nut is consistently below proof load for the bolts with the longer grips. Even at 5/8 turn-of-nut, two lots with long grips had mean loads below the proof load. Although the load at ½ turn-of-nut was above proof load for most of the bolts with short grips, it usually remained within the elastic range and was therefore very sensitive to minor changes in elongation.

The ultimate load in torqued tension was found to be between 77.5% and 92% of the direct tension ultimate for bolts tested with residue oil as the thread lubricant with corresponding figures of 79% and 94.5% for bolts lubricated with multi-purpose type grease. The waxed element tests produced values between 78.5% and 95.5%. If we consider only the results obtained for A490 and A354 BD bolts, the limits are 77.5% to 92%, 79% to 94.5%, and 81% to 95.5% for the same three conditions of thread lubrication. Clearly, the type of thread lubrication had little effect on the ratio of ultimate torqued tension load to ultimate direct tension load. Since current specifications[6] place the proof load of A490 bolts at 80% of their minimum specified tensile strength, it is possible that the ultimate load in torqued tension could be below proof load for minimum strength bolts. (As shown in Table 3, the bolts used in these tests had mean tensile strengths ranging from 102% to 113% of ASTM minimum, the average value being 108.3%).

Figure 9 gives some indication of the possibility of A490 and A354 BD bolts falling below specified proof load. A plot of the average non-dimensional load vs. elongation of bolts in direct tension and bolts in torqued tension is shown as a frame of reference. These are composite results obtained by considering all of the results contained in this report (using only as-received threads in the case of the torqued tension curve).

The distribution of direct tensile strength is designated in Fig. 9 as "a". This shows that only 2.6% of the sample fell below the minimum specified tensile load. Distribution "b" in Fig. 9 shows the frequency distribution of the ultimate torqued tension load for the bolts tested. 1.5% of the sample had a torqued tension strength that was less than proof load.

Distributions "c" and "d" in Fig. 9 show the frequency distribution of bolt tension after tightening the bolt by rotating the nut the specified amount. Distribution "c" shows the results of 165 bolts installed in steel plate (test joints[17] and special jigs). Distribution "d" shows similar results for 106 bolts installed in the hydraulic calibrator. (In each case, as-received threads were used.) These distributions show that at specified nut rotation about 3.2% of the sample installed in steel plate and about 37% of the hydraulic calibrator sample fell below proof load. Bolts installed in the test joints and special jigs are representative of the installation conditions for well compacted joints. The flexibility of the calibrator may make it comparable to some field installations in which conditions are not ideal.

Since the ultimate load in torqued tension may be less than proof load for minimum strength bolts, it seems advisable to consider a minimum preload for installation of A490 bolts somewhat below proof load. Alternatively, the specified ultimate load could be increased and the current preload maintained. This would ensure a torqued tension strength that always exceeded proof load.

However, if bolts installed in the hydraulic calibrator are indicative of some field installation conditions, a decrease in preload below proof load is the only means of ensuring minimum bolt tension. As shown in Fig. 4, and Tables 5 and 6, ½ turn-of-nut induces nearly the same amount of elongation into a bolt regardless of its strength. The corresponding load in the A490 bolt is in some instances below proof load and on the linear portion of the load-elongation curve. It is apparent that an increase in tensile strength will not affect the amount of induced elongation for the specified nut rotation.

The effects of grip length on the load-elongation relationship of the alloy steel bolt are illustrated in Fig. 10 for 7/8-in. A490 bolts. Both lots had the same thread length under nut. The relationship for the shorter bolt, shown by the solid line, has a steeper elastic slope than for the longer bolt; and although the elongations at ½ turn-of-nut are approximately equal for the two lots, the resulting load is above proof load for the shorter grip bolt and below proof load for the longer.

Figure 11 emphasizes the differences resulting from tests of bolts from the same lot with different lengths of thread under the nut. As with direct tension tests, a shorter length of thread under the nut results in a higher ultimate load. The reasons for this are the same as those discussed for the direct tension tests. This behavior was not appreciably affected by thread lubrication.

Nut rotation to failure ranged from 1 to 1-7/8 turns for torqued tension tests with threads as-received, from 1-1/8 to 2 turns for threads lubricated with heavy grease and from $1\frac{1}{4}$ to 3 turns for waxed threads. As was previously pointed out, waxing the threads produced an average increase of $\frac{1}{4}$ turn-of-nut to failure. It should also be noted that there is an increase in nut rotation with an increase in thread length under the nut. This effect was found to be very pronounced for A325 bolts[(1)] but is less so for alloy steel bolts. Increased nut rotation to failure depends directly on the increased elongation capacity of bolts with greater thread length under the nut. The more the bolt stretches, the greater is the nut rotation that must be applied to cause bolt failure.

3.4 COMBINED TORQUED-DIRECT TENSION TESTS

The results of the combined torqued-direct tension tests are shown in Fig. 12. The bolts were first tightened to 5/8 turn from snug and then loaded in direct tension. The transfer from torqued to direct tension is indicated by the sharp turn upward of the load-elongation relationship. The curve then quickly approaches the direct tension curve for the same lot of bolts, shown as a dashed line. The load-elongation relationship in torqued tension with threads as-received is also included as a frame of reference. Bolt fractures were all similar to those in direct tension with no visible influence of torsional shearing stresses.

One lot of A354 BC bolts and three lots of A490 bolts were first tightened to 5/8 turn and then loaded in direct tension. The mean ultimate loads reached during these tests ranged from 97% to 103% of the corresponding values in direct tension.

3.5 REPEATED WRENCH INSTALLATION

Twelve A354 BC and 12 A490 bolts with threads in the as-received condition were tested by repeatedly tightening and then loosening the nut. Long bolts were tightened with 3/4 or 2/3 turn cycles and short bolts with ½ turn cycles. Six A354 BC and 10 A490 bolts with waxed threads were tested in the same fashion. Either ½ turn or 2/3 turn cycles were used.

Figure 13 shows typical results of one lot of A490 bolts tested with as-received threads and with waxed threads. As the plots show, the load at the end of each successive cycle was lower than for the previous cycle for the as-received lot. Note that proof load was achieved only on the first cycle. Bolts from the same lot when waxed had considerably improved characteristics. It took more cycles to fail these bolts and proof load was attained for most of these cycles. Bolts in the as-received condition did not exceed three cycles before failure for bolts tightened with 3/4 turn-of-nut and had an average of four cycles for bolts tightened with ½ turn-of-nut. A490 bolts with waxed threads averaged eight cycles to failure for both ½ turn and 2/3 turn-of-nut.

Whether the threads were waxed or as-received, a marked increase in installation time was noted for successive cycles. In all respects, the behavior of as-received alloy steel bolts under repeated torquing seems to be more critical than that of A325 bolts.(1)

3.6 BOLTS INSTALLED IN STEEL PLATE

Table 7 summarizes the results of tests of bolts installed in steel plates rather than in the hydraulic bolt calibrator. Three A354 BC bolts, 9 A354 BD bolts, and 21 A490 bolts were tested. The table lists mean experimental values of elongation at ½ turn-of-nut, elongation after rupture, and nut rotation to failure. Also listed is the computed load at ½ turn as determined from the measured bolt elongation applied to the mean torqued tension load-elongation curve for tests of the same lot of bolts in the bolt calibrator. This load is then tabulated as a percentage of the load at ½ turn for bolts tested under torqued tension in the bolt calibrator.

The most striking result indicated in the table is that the elongation at ½ turn-of-nut for bolts tightened in solid plate averages about 0.03-in. while in the bolt calibrator the average elongation was closer to 0.02-in. for the same lots (see Table 5). This results in an increase in the load at ½ turn above that found in the bolt calibrator. It appears that the elongation and corresponding tension of a bolt tightened to a given nut rotation in a well compacted joint may be substantially above the values obtained using a hydraulic bolt calibrator. This was also apparent in the frequency distribution shown in Fig. 9. In the last two columns of this table are shown the nut rotations to failure for these tests and those listed in Table 5 for the regular torqued tension tests. It will be seen that in the steel plate, rotation to failure averages about 1/8 turn less than for the tests conducted in the bolt calibrator. It is apparent that the increased deformation of the bolt calibrator results in an increase in the nut rotation required to cause failure.

The results of this type of test are shown in Figs. 14 and 15 for the ED lot of A354 BD bolts torqued in four 4 x 4 x 1-in. plies of A440 steel. At the top of Fig. 14 are plotted the relationships for nut rotation versus elongation. The solid test points are for the bolts tested in the bolt calibrator and the open points are for those tested in the steel plate. Bolts torqued in steel plate to a given nut rotation were more elongated than those torqued in the bolt calibrator with a resulting increased bolt tension.

Ideally, the bolt head, the nut, and the gripped material would be completely rigid and the entire deformation would be in the form of elongation of the bolt shank and threads. For one revolution of the nut, this deformation would be equal to the distance between threads. This ideal behavior is shown as a dashed curve in Fig. 14.

The three curves shown at the top of the figure all originate at the mean snug elongation of 0.0025-in. as measured during the torqued tension calibration. Bolts in the steel plate were purposely snugged to this elongation.

The bottom half of Fig. 14 is the mean relationship between bolt tension and elongation for this lot of bolts in torqued tension. By projecting the elongations from the elongation-rotation curves onto the mean load-elongation curve in the manner shown, load versus nut-rotation relationships can be plotted for the solid plate tests and for the ideal case of completely rigid bolt head, nut, and gripped material. These relationships are plotted in Fig. 15. The shape of the curve for the ideal case is the same as the load-elongation curve since in this case there is a direct relationship between nut rotation and bolt elongation. The computed curve for the solid plates deviates from this curve at a constant rate, indicating the flexibility of the system. Proof load was reached in this case at just over ¼ turn-of-nut. The load-rotation curve obtained in the bolt calibrator is also compared with the ideal and solid plate curves in Fig. 15. This curve indicates the greatest flexibility, with large deformation at small rotation indicating a slight amount of play in the hydraulic system itself, probably due to entrapped air. Proof load was not reached in this case until just under ½ turn-of-nut. These three curves also indicate smaller nut rotations to failure for the stiffer assemblies.

3.7 CONTINUOUSLY TORQUED BOLTS

Two lots of A354 BC and three lots of A490 bolts were torqued continuously to either ½ or 3/4 turn-of-nut to determine whether the bolts were affected by incremental tightening. The resulting variation was no more than ten percent in either direction for load or elongation at the specified number of turns. Similar results were reported in Ref. 1 for A325 bolts.

4. SUMMARY

The following conclusions and recommendations are based upon the tests described in this report.

1. Coupon tests do not accurately reflect the true strength of a bolt when they are cut concentrically with the bolt axis, primarily because of the reduced effect of heat treatment near the center of the bolt. The inaccuracy was more pronounced for the 1-in. bolts than for the 7/8-in. bolts.

2. The elastic behavior of high strength bolts in direct and in torqued tension can be predicted using the simple theory for deformation of axially loaded members.

3. All bolts had lower ultimate loads when tested in torqued tension than in direct tension. Ultimate loads of bolts torqued with residue oil as the only lubricant varied from 78 to 92% of those tested in direct tension, with an average value of about 85%. The use of heavy grease or wax as a thread lubricant resulted in slightly increased torqued ultimate loads for the A354 BD and A490 bolts.

4. A decrease in the length of thread under the nut results in increased ultimate strength and reduced elongation capacity for both direct and torqued tension tests of alloy steel bolts.

5. When bolts were tested in the hydraulic bolt calibrator, the preload induced by ½ turn-of-nut exceeded proof load for all lots of A354 BC bolts and for most of the A354 BD and A490 bolts with short

grip lengths. However, these loads usually remained in the elastic range and were therefore subject to large variations for relatively small variations in elongation. For the A354 BD and A490 bolts with grip lengths above seven inches, proof load could not be induced by ½ turn-of-nut. Even at 5/8 turn-of-nut, the preload induced in the bolt calibrator was often less than proof load.

6. Tests of A354 and A490 bolts tightened in steel plate indicate that fewer turns of nut are required to induce a given preload than in the bolt calibrator. Less nut rotation to failure was also observed in steel plate. These effects are due to the inherent flexibility of the bolt calibrator.

7. The 1-in. A354 BC bolts behaved in a somewhat less ductile manner than 7/8-in. A354 BC bolts. The nut rotation to failure averaged about ¼ turn less for the 1-in. bolts than for the 7/8-in. bolts. This was not the case for the A354 BD and A490 bolts.

8. Except for providing a slightly higher ultimate strength for the A354 BD and A490 bolts, the use of heavy grease or wax as a thread lubricant had little apparent effect on the torqued tension characteristics. Waxing the threads did produce an increase in the number of turns to failure. For the A354 BC bolts, the freshly applied shipping oil seemed to be slightly more beneficial in producing high ultimate loads and large nut rotations to failure than the heavy grease.

9. Nut rotations from snug were found to vary from one to two full turns before bolt failure, increasing with increased

thread length under the nut. In general, the A354 BC bolt withstood more turns to failure than the A354 BD or A490 bolt.

10. Direct tension tests after preloading the bolt indicate that preloading with a wrench does not reduce the tensile strength.

11. Repeated tightening of alloy steel bolts into the inelastic range resulted in a marked reduction in induced tension with each installation and a marked increase in installation time. The use of wax as a thread lubricant prevented the large reduction in induced tension.

12. The behavior of alloy steel bolts torqued continuously to a given nut rotation does not differ from that of incrementally-tightened bolts.

13. Consideration should be given to either specifying an installed preload less than the present proof load for alloy steel bolts or increasing the specified ultimate load so that the present proof load is a smaller percentage of the tensile strength. This would ensure a torqued tension strength that exceeds required minimum bolt tension. However, if bolts installed in the bolt calibrator are indicative of field installation conditions, the installed preload should be less than the present proof load.

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The Russell, Birdsall and Ward Bolt and Nut Co. contributed most of the bolts tested. Bethlehem Steel Co. donated four lots of A490 bolts and also supplied the air compressor and impact wrench. The Skidmore-Wilhelm Co. furnished the Model K hydraulic bolt calibrator.

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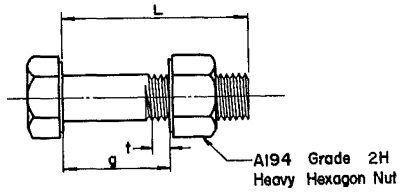
TABLE 1

DESCRIPTION OF SPECIMENS



Bolt Lot	ASTM Designation	Head* Type	Nominal Diameter, inches	Type of Thread	L inches	g inches	t inches
AC-7-2S	A354BC	H	7/8	Cut	5.25	3.62	0.125
AC-7-9S	"	H	7/8	"	"	4.06	0.562
BC-8-2S	"	H	1	"	"	3.37	0.125
BC-8-11S	"	H	1	"	"	3.94	0.688
CC-7-12S	"	R	7/8	Rolled	5.50	4.25	0.75
DC-8-16S	"	R	1	"	"	"	1.00
AD-7-2S	A490	H	7/8	Cut	5.25	3.62	0.125
AD-7-9S	"	H	7/8	"	"	4.06	0.562
BD-8-2S	"	H	1	"	"	3.37	0.125
BD-8-11S	"	H	1	"	"	3.94	0.688
CD-7-2L	"	H	7/8	"	9.25	7.62	0.125
CD-7-9L	"	H	7/8	"	"	8.06	0.562
DD-8-2L	"	H	1	"	"	7.37	0.125
DD-8-11L	"	H	1	"	"	7.94	0.688
ED-7-12S	A354BD	R	7/8	Rolled	5.50	4.25	0.75
FD-8-16S	"	R	1	"	"	"	1.00
GD-7-12L	"	R	7/8	Cut	9.50	8.00	0.75
HD-8-16L	"	R	1	"	"	7.75	1.00
LI-7-2S	A490	H	7/8	Rolled	5.50	4.12	0.125
LI-7-9S	"	H	7/8	"	"	4.56	0.562
AB-7-2L	"	H	7/8	Cut	9.50	8.25	0.125
AB-7-9L	"	H	7/8	"	"	8.69	0.562
KK-7-2S	"	H	7/8	Rolled	5.50	4.19	0.125
JJ-8-6S	"	H	1	"	"	4.12	0.375

*From American Standards Assoc. B18.2: H identifies Heavy Semi-finished Hexagon Head
R identifies Regular Semi-finished Hexagon Head

Table 2

COUPON TEST RESULTS

Bolt Lot	ASTM Designation	Number Tested	Tensile Strength ksi	% ASTM Minimum	Elong. in 1.9"%	% ASTM Minimum	Red. of Area, %	% ASTM Minimum
AC	A354BC	3	140.3	112	21.2	132	57.2	114
BC	"	3	126.2	101	22.1	138	-	-
CC	"	3	133.0	106	21.6	135	62.2	124
DC	"	3	131.6	105	22.6	141	63.1	126
AD	A490	3	162.5	108	18.0	128	-	-
BD	"	3	147.7	98	14.6	104	59.1	169
CD	"	3	156.1	104	18.8	134	59.8	171
DD	"	3	156.6	104	19.8	142	59.8	171
ED	A354BD	3	164.9	110	16.6	118	59.1	169
FD	"	3	149.8	100	16.7	119	58.1	166
GD	"	3	160.9	107	18.8	134	58.1	166
HD	"	3	165.1	110	16.3	116	55.5	159
LI	A490	-	-	-	-	-	-	-
AB	"	3	151.6	101	21.4	153	52.9	151
KK	"	3	153.4	102	20.0	143	55.5	159
JJ	"	-	-	-	-	-	-	-

Table 3

COMPARISON OF BOLTS TO ASTM SPECIFICATIONS

Bolt Lot	ASTM Designation	Hardness, Rockwell C		Hardness, Brinell		Tensile Strength*		
		Stand. Proc.	Arbit. Method	Stand. Proc.	Arbit. Method	No. Tested	Mean, kips	% ASTM Minimum
AC-7-9S	A354BC	30	-	269	-	3	65.0	113
BC-8-11S	"	30	-	281	-	3	82.9	109
CC-7-12S	"	31	34	277	277	3	62.3	108
DC-8-16S	"	32	37	288	331	3	83.1	110
AD-7-9S	A490	34	37	329	335	3	76.5	110
BD-8-11S	"	35	40	328	341	3	100.0	110
CD-7-9L	"	35	35	328	321	3	74.5	108
DD-8-11L	"	34	-	304	-	3	96.7	106
ED-7-12S	A354BD	38	44	338	352	3	77.8	112
FD-8-16S	"	37	-	331	-	3	99.3	109
GD-7-12L	"	32	40	331	331	3	75.5	109
HD-8-16L	"	36	38	332	352	3	100.5	110
LI-7-9S	A490	34	40	318	331	5	72.1	104
AB-7-9L	"	34	37	307	321	5	70.8	102
KK	"	35	38	323	331	1	72.3+	104
JJ	"	35	40	323	341	2	94.8+	104

*All results shown here are for six threads under the nut as specified in ASTM A370

+From mill report

Table 4

DIRECT TENSION TEST RESULTS

Bolt Lot	ASTM Designation	Proof Load kips	Number of Specimens Tested	Ultimate Load Mean kips	Ultimate Load % ASTM Minimum	Rupture Load kips
AC-7-2S	A354BC	48.50	3	72.6	126	64.3
AC-7-9S	"	48.50	3	65.0	113	52.0
BC-8-2S	"	63.65	3	91.0	120	76.3
BC-8-11S	"	63.65	3	82.9	109	61.7
CC-7-12S	"	48.50	3	62.3	108	48.7
DC-8-16S	"	63.65	3	83.1	110	64.0
AD-7-2S	A490	55.45	3	83.1	120	78.3
AD-7-9S	"	55.45	3	76.5	110	68.7
BD-8-2S	"	72.70	3	102.1	112	92.0
BD-8-11S	"	72.70	3	100.0	110	92.3
CD-7-2L	"	55.45	3	82.6	119	79.2
CD-7-9L	"	55.45	3	74.5	108	69.8
DD-8-2L	"	72.70	3	105.4	116	93.3
DD-8-11L	"	72.70	3	96.7	106	85.3
ED-7-12S	A354BD	55.45	3	77.8	112	71.7
FD-8-16S	"	72.70	3	99.3	109	81.3
GD-7-12L	"	55.45	3	75.5	109	71.0
HD-8-16L	"	72.70	3	100.5	110	91.7
LI-7-2S	A490	55.45	5	76.0	110	67.0
LI-7-9S	"	55.45	5	72.1	104	59.0
AB-7-2L	"	55.45	5	73.2	106	65.0
AB-7-9L	"	55.45	5	70.8	102	61.0
KK-7-2S	"	55.45	5	77.9	112	69.3
JJ-8-6S	"	72.70	5	99.2	109	85.0

Table 5 Torqued Tension Test Results

Bolt Lot	THREADS AS-RECEIVED								THREADS WITH HEAVY GREASE							
	No. Spec.	Load at ½ turn kips	Load at 5/8 turn kips	Ult. Load kips	% Direct Tension Ult.	Rupture Load kips	Elong. at ½ turn in.	Nut Rotat. To Failure revs.	No. Spec.	Load at ½ turn kips	Load at 5/8 turn kips	Ult. Load kips	% Direct Tension Ult.	Rupture Load kips	Elong. at ½ turn in.	Nut Rotat. To Failure revs.
AC-7-2S	3	49.1	57.6	61.3	84.5	47.0	.0128	1-1/2	3	51.5	55.1	62.5	86.0	44.3	.0130	1-5/8
AC-7-9S	3	52.8	55.1	56.5	87.0	36.7	.0260	1-3/4	3	52.0	54.9	56.8	87.5	40.3	.0225	1-3/4
BC-8-2S	3	75.3	77.8	78.5	86.5	43.3	.0202	1-1/4	3	74.2	71.7	76.5	84.0	52.0	.0208	1-1/4
BC-8-11S	3	70.2	72.2	72.7	88.0	55.3	.0291	1-1/4	3	67.2	69.7	71.5	86.5	51.3	.0220	1-1/2
CC-7-12S	3	51.1	53.6	55.7	89.5	40.3	.0227	1-7/8	3	50.8	53.0	55.2	89.0	43.0	.0231	1-7/8
DC-8-16S	3	70.8	73.5	74.5	90.0	49.7	.0299	1-3/4	3	70.2	72.8	73.7	89.0	54.7	.0243	1-3/4
AD-7-2S	3	48.9	62.8	70.5	85.0	58.0	.0127	1-1/4	3	60.3	72.1	78.6	94.5	59.3	.0152	1-1/2
AD-7-9S	3	60.9	64.8	66.9	87.5	53.0	.0209	1-3/8	3	58.0	62.4	65.8	86.0	50.3	.0199	1-5/8
BD-8-2S	3	84.5	90.7	90.7	89.0	71.7	.0181	1	3	83.5	90.2	91.3	89.5	73.7	.0178	1-1/8
BD-8-11S	3	72.5	80.5	83.0	83.0	58.0	.0173	1-3/8	3	68.0	77.7	78.8	79.0	60.3	.0170	1-3/8
CD-7-2L	3	45.7	50.1	71.9	87.0	66.7	.0219	1-3/8	3	47.8	58.9	76.1	92.0	58.0	.0228	1-3/4
CD-7-9L	4	46.9	55.7	62.6	84.0	56.2	.0240	1-1/4	3	46.7	55.8	66.6	89.5	56.3	.0239	1-1/2
DD-8-2L	3	64.0	80.0	90.3	85.5	70.7	.0223	1-1/4	3	58.3	79.5	99.0	94.0	77.0	.0201	1-5/8
DD-8-11L	3	67.0	78.8	84.0	87.0	59.7	.0262	1-5/8	3	69.7	80.3	85.0	88.0	58.7	.0269	1-3/4
ED-7-12S	4	59.2	64.0	67.6	87.0	52.8	.0183	1-3/8	3	61.9	66.8	68.5	88.0	58.0	.0192	1-1/2
FD-8-16S	3	77.8	83.8	88.2	89.0	68.8	.0222	1-3/8	3	61.3	77.2	85.5	86.0	66.3	.0164	1-7/8
GD-7-12L	3	32.7	42.6	69.3	92.0	58.0	.0155	1-3/4	3	36.1	45.8	68.1	90.5	60.3	.0163	1-5/8
HD-8-16L	3	66.7	81.5	91.2	91.0	75.3	.0250	1-3/4	3	61.7	78.3	90.3	90.0	68.0	.0236	1-7/8
LI-7-2S*	5	53.4	59.9	61.1	80.5	40.0	.0162	1-1/4	3	48.5	57.5	60.5	79.5	42.2	.0139	1-1/8
LI-7-9S*	5	50.0	55.4	58.4	81.0	34.0	.0156	1-5/8	3	50.5	57.1	62.4	86.5	43.0	.0162	1-3/4
AB-7-2L*	6	48.6	57.5	65.4	89.0	52.0	.0235	1-3/8	3	44.5	56.4	70.2	96.0	44.4	.0216	1-5/8
AB-7-9L*	5	41.1	50.8	61.8	87.0	50.0	.0219	1-3/4	3	46.8	54.9	64.4	91.0	48.3	.0224	1-3/4
KK-7-2S	10	56.2	60.2	60.4	77.5	47.5	.0182	1	-	-	-	-	-	-	-	-
JJ-8-6S*	5	81.0	85.8	87.3	87.5	64.0	.0201	1-1/2	3	75.0	82.0	86.0	86.5	59.8	.0180	2

* Snug load was taken at 10 kips for these lots.

Table 6

TORQUED TENSION TEST RESULTS
THREADS WAXED

Bolt Lot	Number of Specimens Tested	Load at ½ kips	Load at 5/8 Turn kips	Ultimate Load Mean kips	Ultimate Load % Dir. Tens. Ult.	Rupture Load kips	Elong. At ½ Turn in.	Nut Rotation to Rupture revs.
AC-7-2S	3 WB	46.7	53.5	57.0	78.5	47.3+	.013	1-1/2*
	3 WN	54.3	57.8	60.3	83.0	30.2+	.016	1-5/8*
CC-7-12S	3 WB	47.5	52.3	54.4	87.0	37.6	.014	2-5/8
	3 WN	47.2	51.6	55.4	89.0	22.0+	.013	3 *
AD-7-2S	1 WB	51.5	61.6	67.2	81.0	44.0+	.014	1-3/8*
	3 WN	53.5	61.3	67.7	81.5	48.4+	.016	1-3/8*
AD-7-9S	3 WB	57.7	63.2	65.9	86.0	55.0+	.017	1-3/8*
	3 WN	50.5	58.1	66.8	87.0	47.4+	.015	1-3/4*
DD-8-2L	3 WB	73.1	89.3	100.6	94.5	85.2	.025	1-3/8
	3 WN	75.7	91.0	98.9	94.0	43.0+	.026	1-3/8*
DD-8-11L	3 WB	69.3	84.0	92.8	96.0	74.7	.027	1-3/4
	3 WN	82.0	88.9	92.3	95.5	74.7	.031	1-5/8
ED-7-12S	3 WB	56.0	61.7	69.2	89.0	52.6	.011	2-1/8
	3 WN	54.8	62.7	70.9	91.0	55.0	.016	2
GD-7-12L	3 WB	38.0	47.8	65.5	87.0	54.2	.020	2-1/8
	3 WN	38.4	48.2	66.9	88.5	43.5+	.022	2-1/4*
LI-7-2S	3 WB	58.0	63.3	67.7	89.0	63.5+	.015	2-1/8*
	3 WN	55.0	63.2	67.0	88.0	40.0+	.016	1-3/8*
LI-7-9S	3 WB	48.5	56.3	61.5	85.0	57.2+	.015	1-1/4*
	3 WN	55.3	62.9	65.7	91.0	52.3+	.017	1-1/2*
AB-7-2L	3 WB	45.8	55.5	67.1	92.0	51.2+	.023	1-3/8*
	3 WN	54.5	63.2	69.3	94.5	52.3+	.027	1-1/2*
AB-7-9L	3 WB	39.8	47.9	62.5	88.5	45.5+	.021	1-5/8*
	3 WN	51.7	58.9	63.8	90.0	44.2+	.027	1-5/8*

+at stripping

*revs. to stripping

Note: If two or more of the 3 tests are stripping failures, this is what is reported

WB = waxed bolt
WN = waxed nut

TABLE 7

BOLTS INSTALLED IN STEEL PLATE

Bolt Lot	Number of Specimens Tested	Elong. at 1/2 turn of Nut, inches	Computed Load at 1/2 turn of Nut, kips	% of Load at 1/2 turn from Table 5 (As-received)	Elong. after Rupture, inches	Nut Rotation to Rupture, revs.	Nut Rotation to Rupture from Table 5 (Heavy-grease)
BC-8-11S	3	.0392	71.6	102	0.093	1	1-1/4
BD-8-2S	3	.0286	89.5	106	0.070	1	1
BD-8-11S	3	.0386	82.0	113	0.097	1	1-3/8
ED-7-12S	3	.0346	65.5	110	0.117	1-1/8	1-3/8
FD-8-16S	3	.0282	83.0	107	0.183	1-3/4	1-3/8
GD-7-12L	3	.0359	63.0	192	0.137	1-1/2	1-3/4
LI-7-12S	5	.0286	60.5	113	0.096	1-1/4	1-1/4
LI-7-9S	5	.0229	57.3	114	0.100	1-1/2	1-5/8
KK-7-2S	5	.0248	59.5	106	0.060	7/8	1

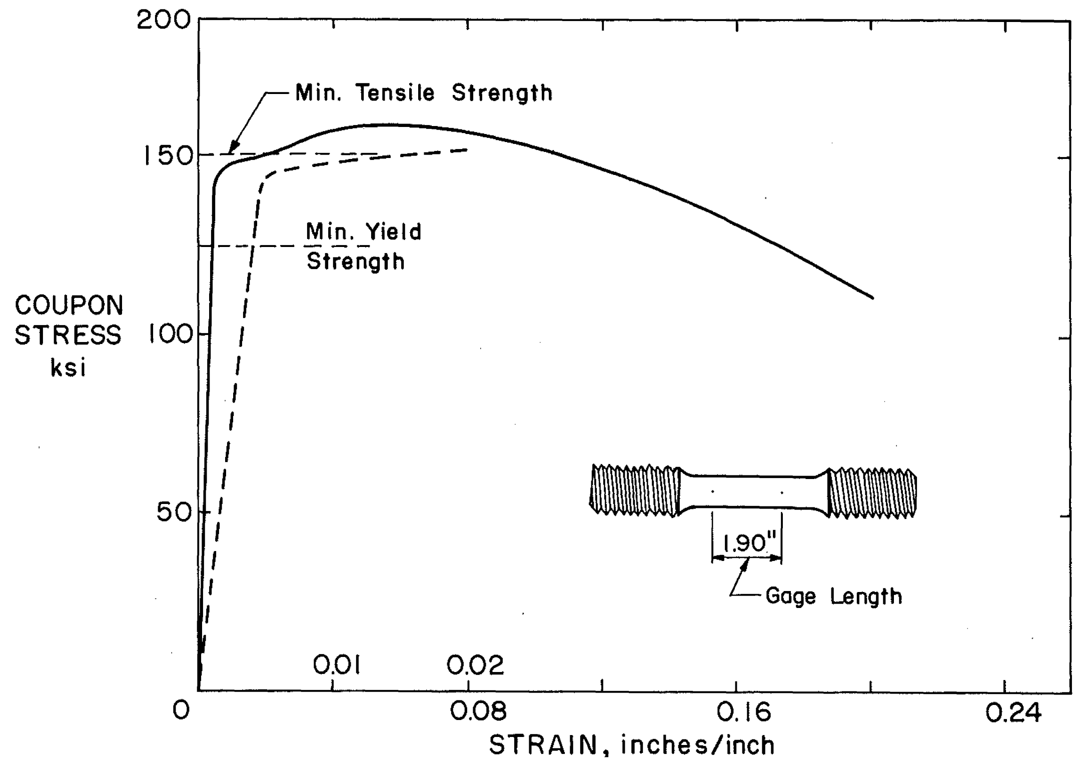


Fig. 1 Coupon Stress-Strain Relationship

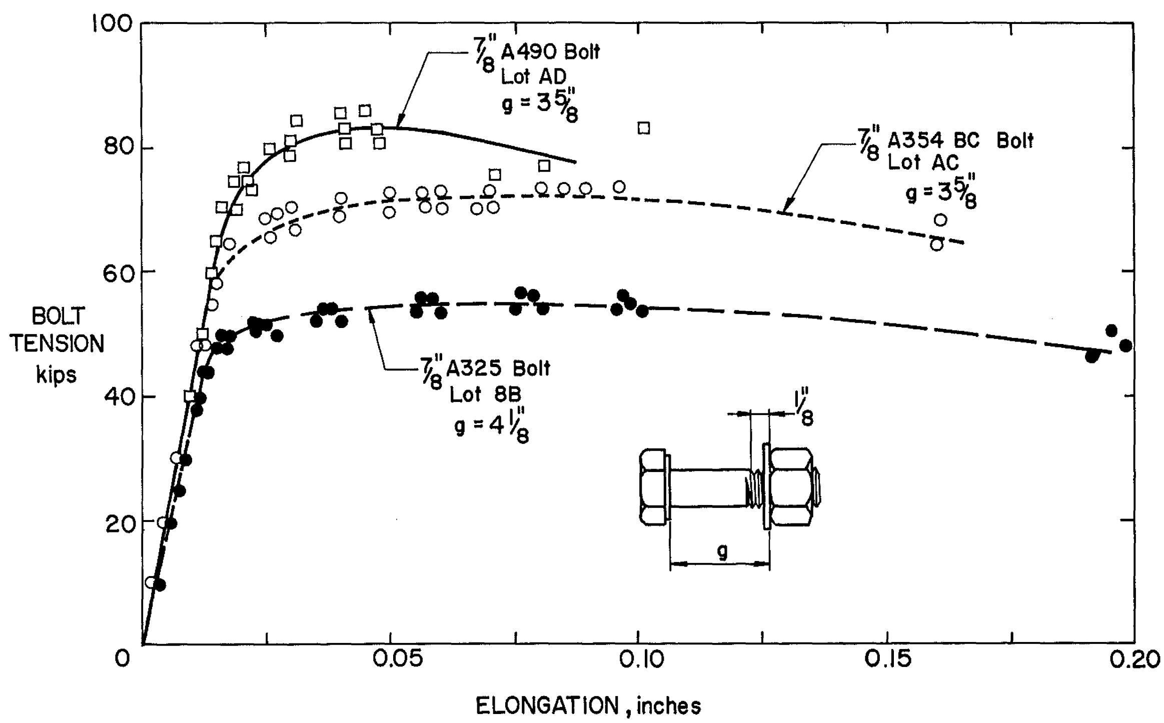
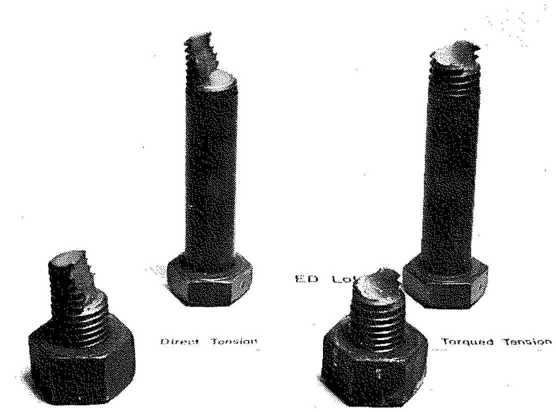
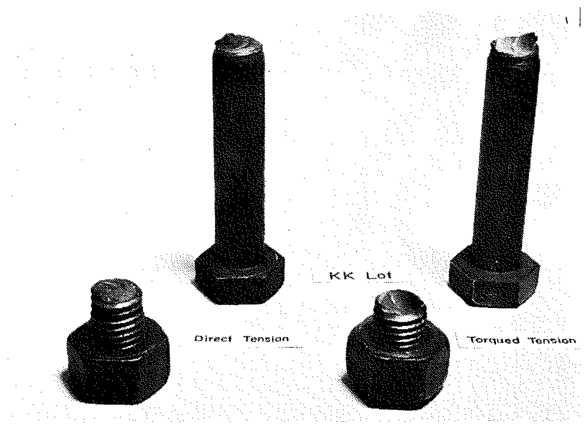


Fig. 2 Comparison of Bolt Types, Direct Tension



a) Long Threads



b) Short Threads

Fig. 3 Bolt Fractures

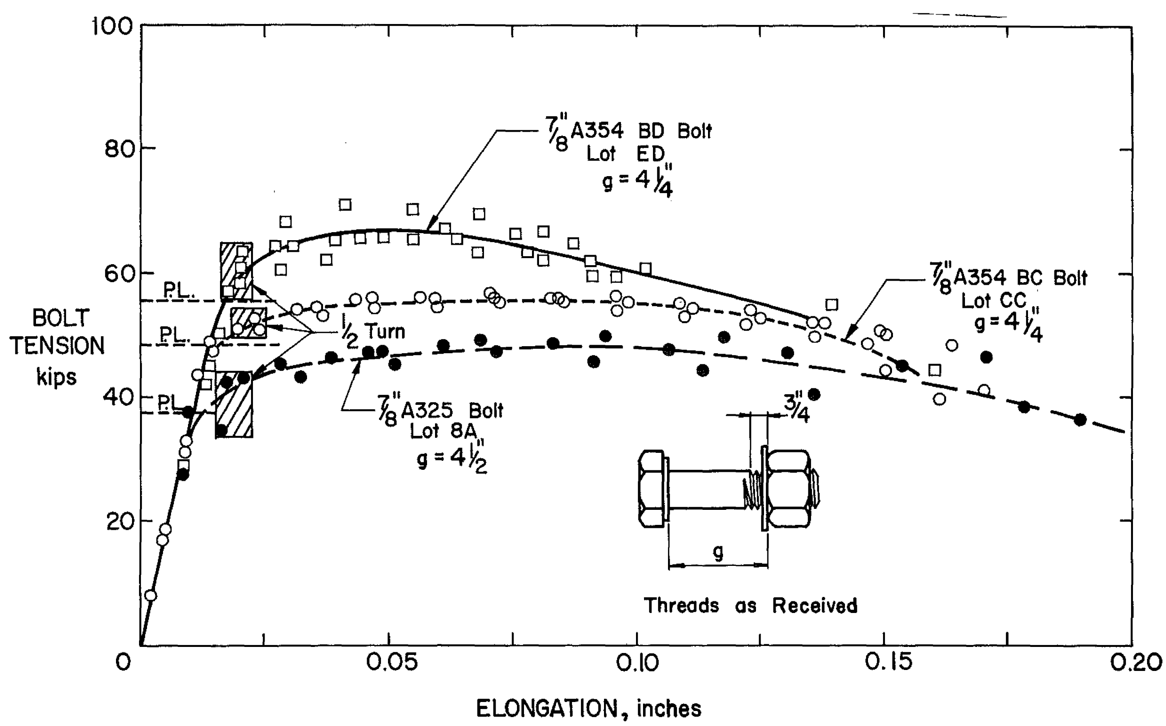


Fig. 4 Comparison of Bolt Types, Torqued Tension

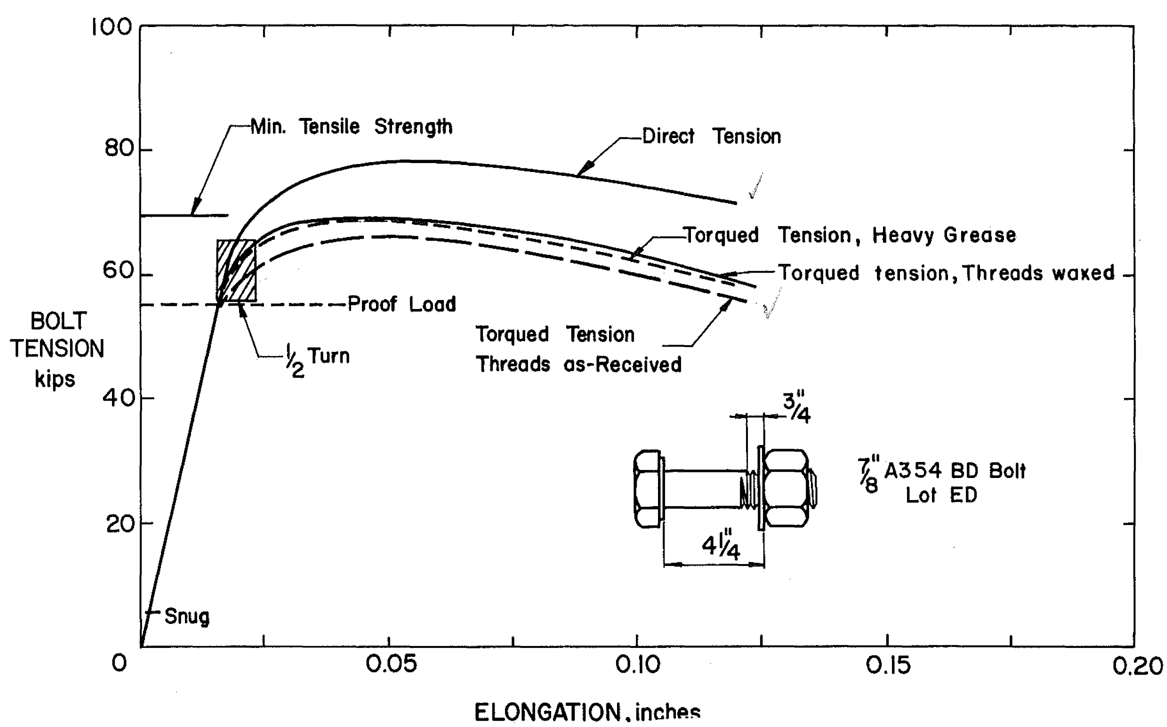


Fig. 5 Comparison of Loading Methods, Effect of Lubrication

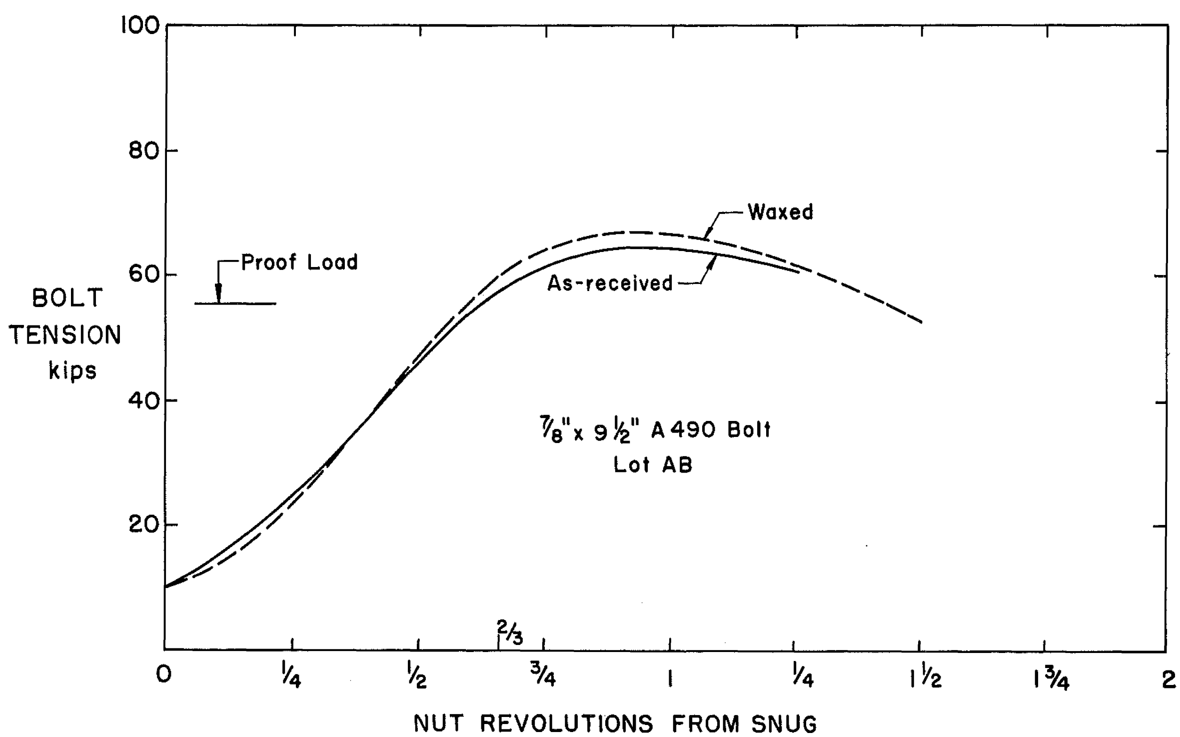


Fig. 6 Effect of Thread Lubrication Upon Nut Rotation

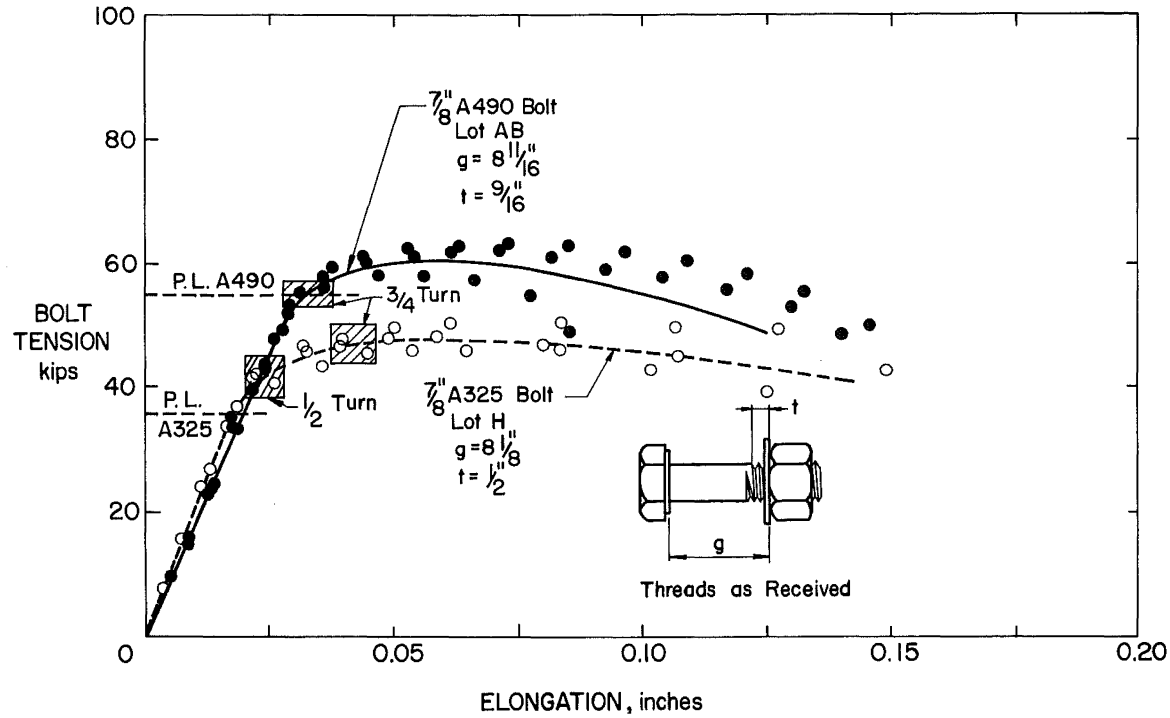


Fig. 7 Long Bolts, A325 vs. A490, Torqued Tension

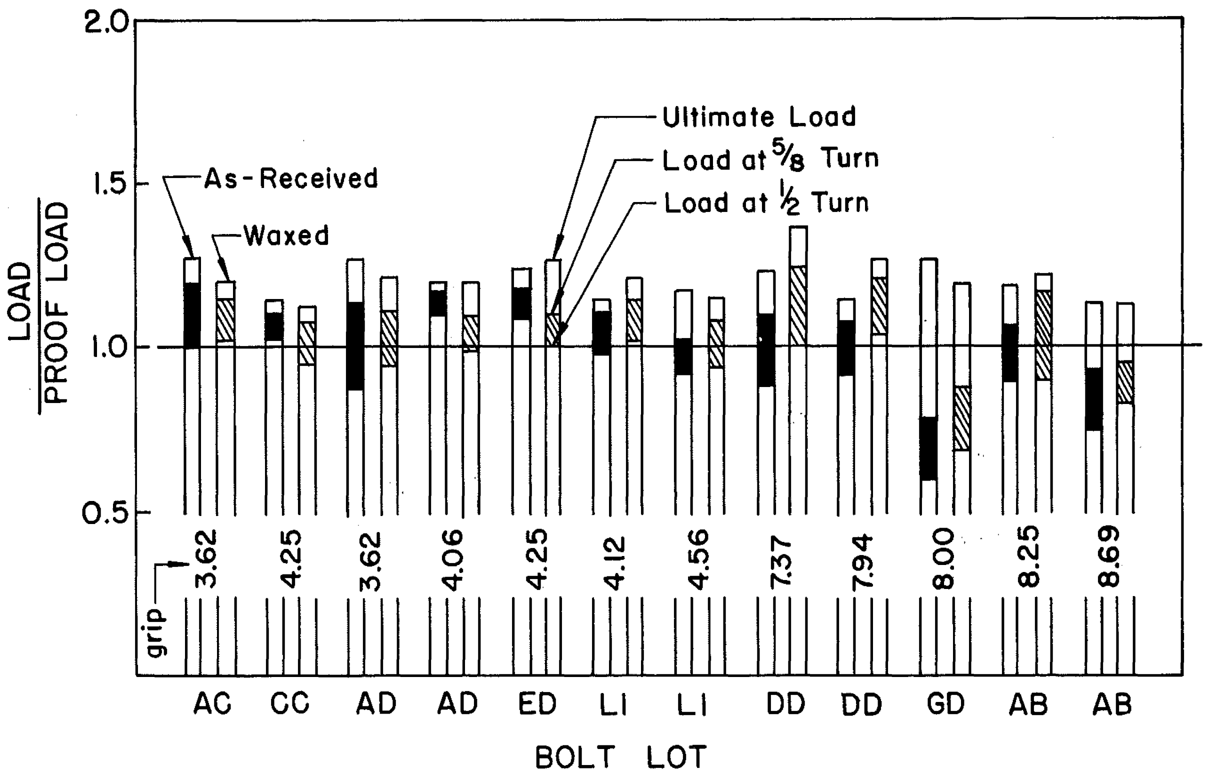


Fig. 8 Load at Specified Nut Rotation

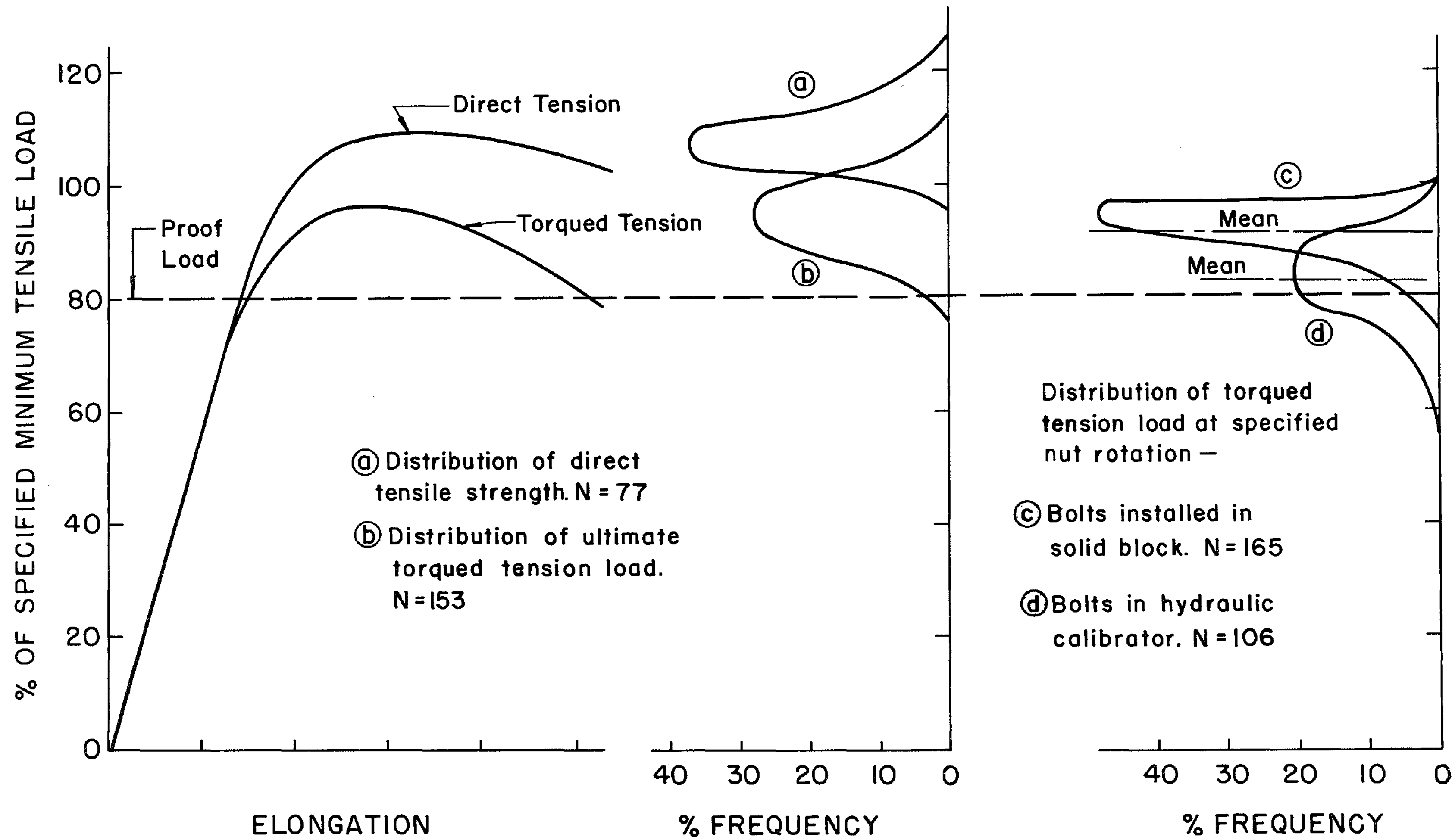


Fig. 9 Frequency Distribution of Bolts Tested in Torqued Tension and in Direct Tension

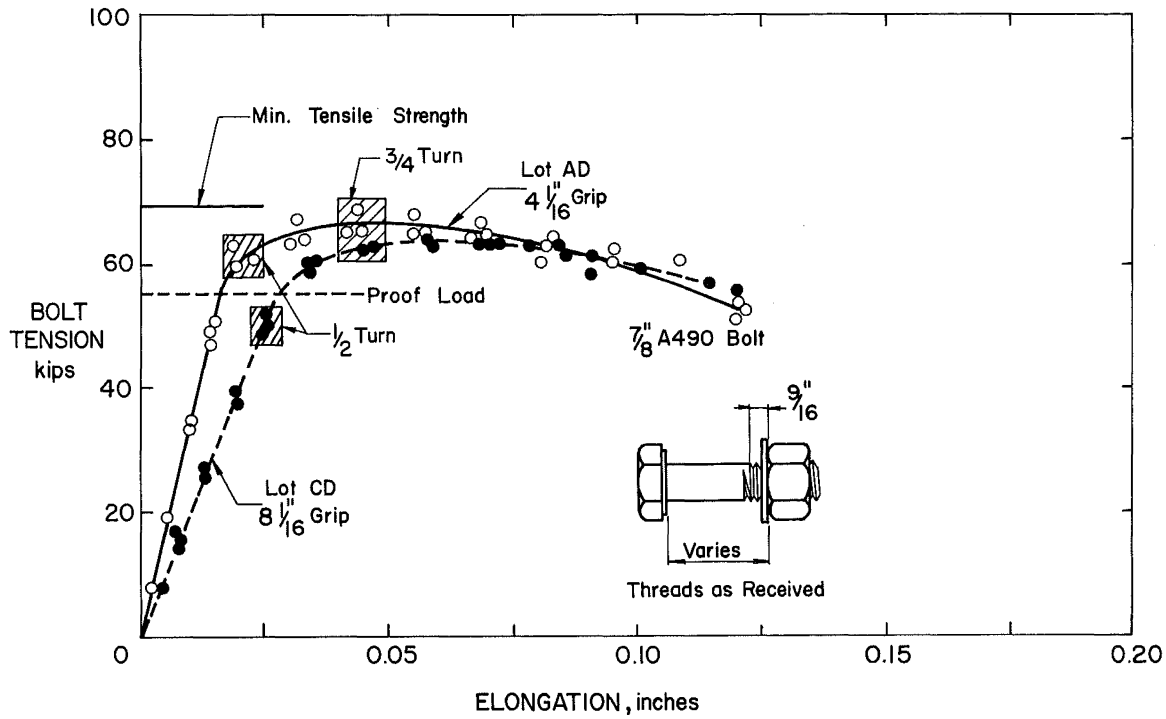


Fig. 10 Effect of Grip Length

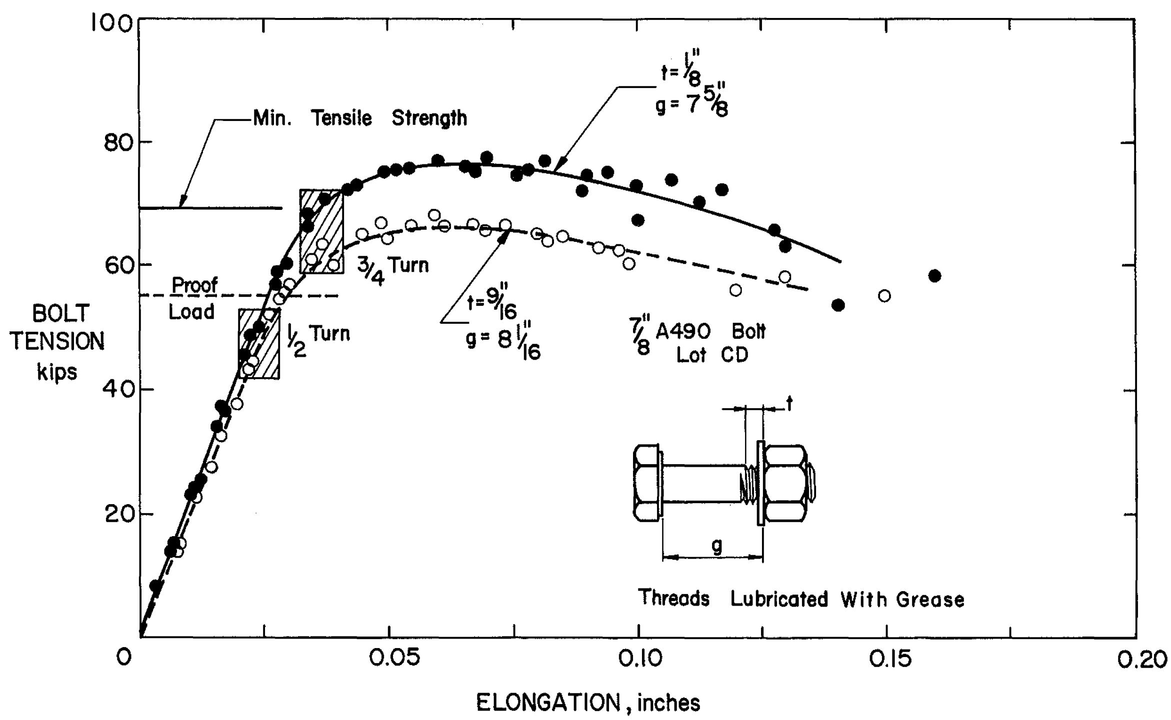


Fig. 11 Effect of Thread Length Under Nut, Torqued Tension

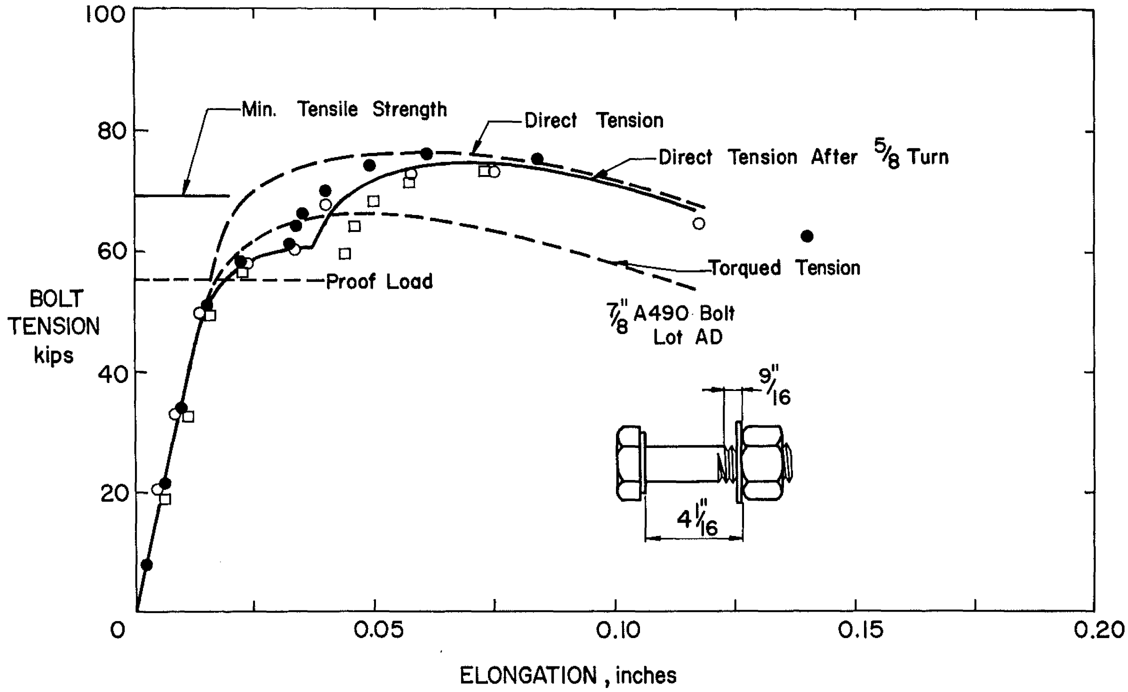


Fig. 12 Reserve Tensile Strength of Torqued Bolts

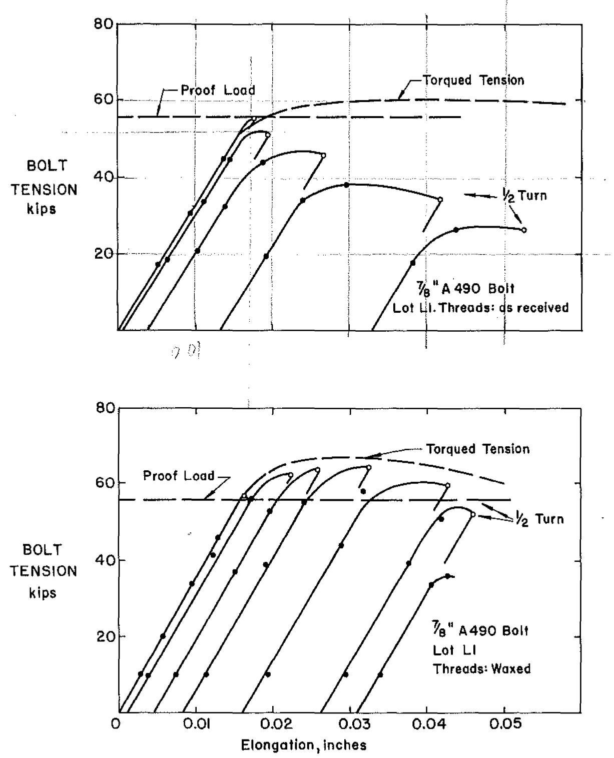


Fig. 13 Repeated Installation of Bolts, ½ Turn-of-Nut

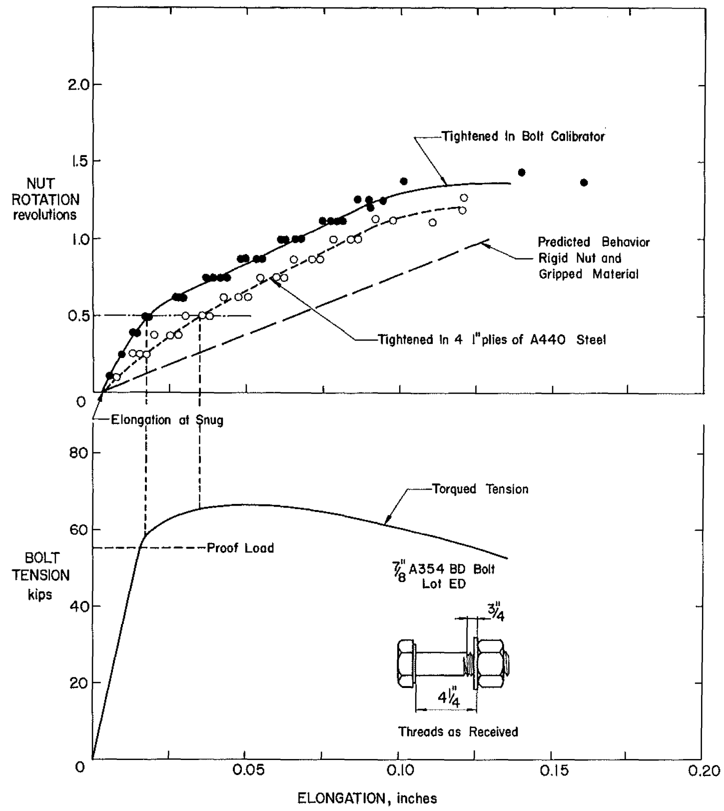


Fig. 14 Bolts Torqued in Steel Plates

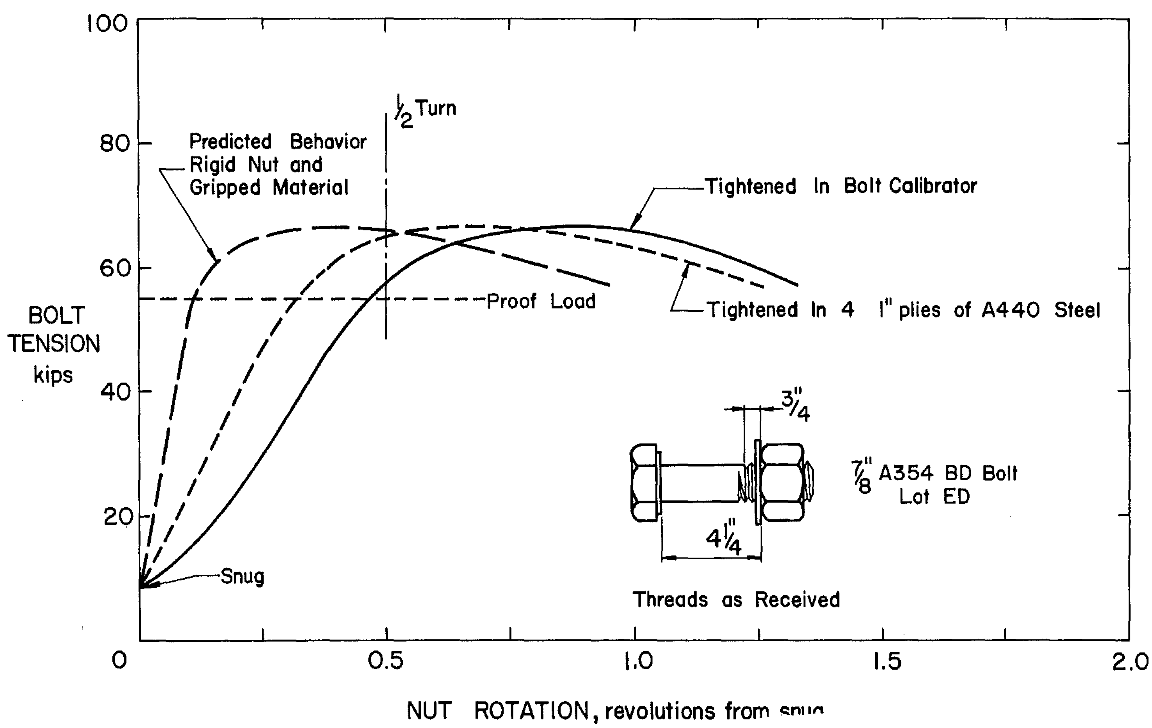


Fig. 15 Tension - Nut Rotation Relationships

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The performance of alloy steel structural bolts when subjected to various conditions of installation and load was determined. The bolts investigated were ASTM A354 Grades BC and BD and ASTM A490. Variables included bolt diameter, grip length, thread length under nut, and thread lubrication. The problems investigated in the 120 direct tension tests and 174 torqued tension tests included the behavior of a bolt loaded in tension by either direct axial force or by torque, the response of bolts installed by torquing to subsequent application of direct tension, the effect of reinstallation, differences between tests performed in a hydraulic load cell and field behavior of the bolts, differences between incremental torquing and continuous torquing, and the effect of thread lubrication. Conclusions and recommendations are made concerning alloy steel bolts and their performance as structural fasteners.

KEY WORDS: bolts; steel; structural engineering; testing.