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Long Bolted Connections

CALIBRATION OF ALLOY STEEL BOLTS

by

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SYNOPSIS

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 prime objective of this study is the investigation of 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 for several reasons. 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 tensile behavior of a bolt loaded by either a direct axial force or by a combination of the two.

In addition to the basic tensile behavior, several other problems deserve attention. How will an alloy steel bolt installed with a wrench react to directly applied tensile forces? How often can these bolts be reinstalled? Is the relationship between nut rotation and bolt load significantly affected when the bolt is wrench-tightened in an actual joint rather than in a hydraulic load cell?

Do these bolts react any differently when tightened continuously to a given nut rotation than they do when tightened incrementally, as most experimental procedures require? These problems will be discussed in this report.

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 Ref. 4.

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(5), and eight lots conforming to the A490(6) specification for quenched and tempered alloy steel structural bolts. The A490 specification calls for the heavy head and short thread length of A325(7) specification 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 Canadian bolts manufactured to AISI specification 4140.

Both 7/8 and 1 in. heavy and regular semi-finished hexagon head bolts were tested. ASTM A194(8) grade 2H nuts with heavy semi-finished hexagon 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[9].

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 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 specification 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 a complete lack of shipping oil on the A354 BC grade bolts.

The overall test program was planned to investigate the previously discussed major and secondary types of tensile behavior of these bolts. Bolt coupon and hardness tests were conducted to establish trends based on the physical properties specified by ASTM. Table 2 lists in condensed form the physical properties specified by ASTM for the 7/8 and 1 in. bolts. In addition to the properties called for in the A354 and the A490 specifications, the corresponding values from the A325 specification are listed for comparison.

In planning the program, emphasis was placed on the determination of basic tensile behavior in both direct and torque-induced tension. Torqued tension tests of the A354 BC bolts could not be completed until the threads were covered with a light, water-soluble shipping oil. These bolts were received without any trace of lubrication and before this oil was applied, threads seized at applied loads as low as ten kips. Because of this behavior, a complete series of torqued tension tests was conducted with a heavy multi-purpose grease-type lubricant applied to the threads of both nuts and bolts, to observe the effect of a lubricant heavier than shipping oil.

In addition to these basic tests, several special tests were conducted without heavy lubricant to investigate the problems discussed earlier.

2. TEST PREPARATION AND PROCEDURE

2.1 PREPARATION OF BOLTS

Before testing, all bolts were stamped with their lot designations and with a number to identify them within their lot. Holes were then drilled with a combination drill and countersink in the center of each end of the bolt. These holes provided rings of contact for the tips of the C-frame extensometer at the interface of the drilled and the countersunk portions. This type of contact was protected from damage and gave consistent readings insensitive to minor inclusions of dirt. Reference 1 gives a more detailed description of this preparation.

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. Only those bolts and nuts with proper thread fit were used in the testing program.

2.2 TESTING EQUIPMENT

Bolt coupons were tested in a 60 kip universal testing machine, using threaded tension grips to hold the coupons and a Peters extensometer or autographic recorder to measure their elongation.

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

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 the tests of 7/8 in. bolts[10]. 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 and a better resistance to torque, 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.

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

Additional details of the testing equipment are given in Ref. 1. Also, photographs of the testing devices are shown.

2.3 COUPON AND HARDNESS TESTING PROCEDURES

Coupon and hardness tests were conducted according to the applicable testing procedure specified in ASTM Designation A370[11]. Coupons of 0.505 in. in diameter were prepared and tested at an indicated strain rate of approximately 0.02 inches 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 elongations 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. A belt grinder was used to remove all scale from the areas to be tested and to obtain a smoothly polished surface. Heat input was kept to a minimum by using water during the grinding operation. 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 nut in the desired position. 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 if 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, and 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 only 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 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.

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.

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 small bolt calibrator because it was the only one which was adapted to the oil pump. Because of this, the tests were limited to 7/8 in. bolts. The bolts were first loaded exactly as described above for torqued tension tests until 5/8 turn-of-nut was reached. Then the oil pump was 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 then 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 until all load was removed. This procedure was repeated until bolt failure. Final load, elongation, and number of cycles to failure were than recorded. These tests were conducted to determine the effects of reinstallation of alloy steel bolts in the field. Heavy thread lubricant was not used for these tests.

Several bolts were installed in steel plates and bolt load could not be 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^{o} increments. Elongation was measured at each increment. The LI bolts were tested in a 4 in. square block of A440 steel with a 15/16 in. hole through it. The ED bolts were tested in four 1 in. plies of A440 steel having the same overall dimensions as above. All 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. Again, in these tests the threads were lubricated only with shipping oil.

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; and 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 3 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 two 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 of A490 bolts.

Table 4 lists the results of the Brinell and Rockwell C hardness tests for each bolt lot. These values all fall within the range specified in the applicable ASTM specifications. This table also gives the tensile strength for each lot of bolts. Tensile strength is discussed in more detail in the next section. It is mentioned here only to point out that there is no good correlation between the higher hardnesses and the higher tensile strengths reported; and the hardness values do not compare consistently with each other. However, the results do serve their intended purpose in checking that the bolts met ASTM specifications.

3.2 DIRECT TENSION TESTS

Figure 2 shows typical results of direct tension tests of the A354 BD bolt. The bolt was 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 approximately six threads under the nut as specified by ASTM A370. The ultimate tensile strength for each of these lots is reported in Table 4 along with the percent of that specified by ASTM. 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 3, it will be noticed that there is usually close agreement between the two. The largest discrepancies occur for the one 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 5 contains all test results for all bolts tested in direct tension, including tensile strength and its standard deviation; load at rupture; and elongations at proof load, ultimate load and rupture load.

A study of Table 5 indicates 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 somewhat larger cross sectional area. The strength may also be higher because 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 nut and 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.

A comparison of the behavior in direct tension of the A325, A354BC and A490 (or A354BD) bolts is made in Fig. 4. 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.

Although a threaded fastener is not a simple tension bar, its elastic behavior may be computed by using a few simplifying assumptions. First the threaded portion is considered as a uniform shaft having a cross-sectional area equal to the stress area listed in the applicable ASTM specification. Secondly it is assumed that the full tensile load in the bolt is carried between the inner face of the bolt head and a point centered between the two faces of the nut. It is further assumed that no stress causing axial deformation exists beyond these limits. The total elongation of the bolt as measured by the C-frame extensometer at any given elastic load can then be computed from the formula:

$$\delta = \frac{P}{E} \sum \frac{L}{A}$$

where δ = total axial deformation in in.,

P = axial load in kips,

E = modulus of elasticity in kips per sq. in.,

L = length in in., and

A = cross sectional area in sq. in.

Table 6 lists the computed elongations at proof load for both direct and torqued tension tests. The computed values were within 8% of the measured values for the direct tension tests.

3.3 TORQUED TENSION TESTS

Two series of torqued tension tests were conducted, one with a heavy commercial lubricant applied to the threads of bolt and nut and the other with only a light shipping oil, or simulated shipping oil in the case of the four lots of A354 BC bolts. In all other respects the procedures of the two series were identical. Figure 5 shows the load-elongation relationship in torqued tension with threads as received for the ED lot A354 BD bolt. The load at 1/2-turn is just above proof load.

Table 7 shows the results of torqued tension tests of bolts coated with shipping oil, while Table 8 lists the results of tests of bolts coated with the heavy lubricant. These tables show the mean values of load at 1/2 turn-of-nut from snug, torqued tensile strength, rupture load; and the elongations at proof load, at 1/2 turn-of-nut, at ultimate load, and after rupture. The nut rotation from snug to failure is also listed as are the standard deviation of the mean values of tensile strength and the torqued ultimate load expressed as a percentage of the ultimate load in direct tension for the same lot. In addition to these values, Table 7 reports load and elongation at 5/8 turn-of-nut from snug. These values are reported because they are the closest available to the 2/3 turn specified in the 1964 specification of the Research Council for bolts having lengths under head greater than eight inches or eight diameters whichever is smaller.

The mean curves of Figs. 2 and 5 and the mean curve in torqued tension with lubricated threads are shown in Fig. 6 for comparison of the results of the different types of tests. 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]. Thread lubrication had little effect on the torqued tension behavior.

The lower tensile strength of bolts in torqued tension has been explained theoretically with the principal stress theory[12][13] and the principal strain theory[12]. Lubrication could allow a higher ultimate tensile strength because the shear stress component induced by torque may be reached. Lubrication is thought to have a small effect because the high bearing stresses encountered cause the structures of the lubricant to break down[13].

The reduction in tensile strength occurred in all of the torqued tension tests listed in Tables 7 and 8. The percentage that torqued tension ultimate strength is of direct tensile strength, recorded in both tables, averages about 85% for threads coated with shipping oil and about 88% for heavily lubricated threads. For the A354 BC bolt, proof load is 84% of specified tensile strength and for the A354 BD and A490 bolts it is 80% of specified tensile strength.

Had the bolts tested in this program been minimum strength bolts, some of the lots might have had ultimate strengths in torqued tension below proof load. Regardless of the nut rotation specified, proof load could not be induced in such bolts.

Figure 7 allows comparison of 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 4-1/4 or 4-1/2 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. 4.

Another interesting point is that the mean elongation at 1/2 turn, given in Tables 7 and 8, 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. 8 compares the torqued tension behavior of A325 bolts with a grip length of 8-1/4 in. with that of A490 bolts with a grip length of 9-11/16 in. The elongation and load at 1/2 turn of nut are nearly identical for the two bolt lots. The 1/2 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 increase 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 study of Fig. 9 yields further interesting information. This figure derived from Table 7, is a bar graph of the loads at 1/2 and 5/8 turn and the ultimate load for the A354 BD and A490 bolts for torqued tension tests with threads as received. The load scale is non-dimensionalized by dividing all loads by the proof load so that 7/8 and 1 in. bolts may be compared. The ultimate load is shown to indicate the remaining load available at 1/2 and 5/8 turn-of-nut. The load at 1/2 turn-of-nut is consistently below proof load for the bolts with longer grip lengths for the reasons just presented. Even at 5/8 turn-of-nut, two of the lots with longer grips had mean loads below proof load. Thread length under the nut showed no consistent effect on the loads at 1/2 and 5/8 turn. Table 8 shows that thread lubrication did nothing to improve this behavior. Although the load at 1/2 turn-of-nut was above proof load for most of the bolts with short grip lengths, it usually remained within the elastic range and was therefore very sensitive to minor changes in elongation.

The effects of grip length on the load-elongation relationship of the alloy steel bolt are illustrated in Fig. 10 for two lots of

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 that for the longer bolt; and although the elongations at 1/2 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.

The elastic deformation of bolts in torqued tension is nearly the same as in direct tension and can be computed in the same way. Table 6 shows the comparison between the computed values of elongation at proof load and the measured values in torqued tension taken from Tables 7 and 8. For bolts in which inelastic deformations are not present, the induced preload due to a specified elongation can be predicted reasonably well.

Figure 11 emphasizes the differences resulting from tests of bolts from the same lot with different lengths of thread under the nut. As with the 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 for the direct tension tests. This behavior was not appreciably affected by thread lubrication.

The nut rotation to failure ranged from 1 to 1-7/8 turns for torqued tension tests with threads as received and from 1-1/8 to 1-7/8 turns with lubricated threads. Lubrication had no significant effect on the rotation to failure. The nut rotation to failure is plotted versus the thread length under nut for the 7/8 in. bolts in Fig. 12 Mean curves are shown in the figure, one for A354 BC bolts, one for A354 BD and A490 bolts, and one taken from Ref. 1 for A325 bolts. In all three cases there is an increase in the nut rotation to failure with an increase in the thread length under the nut. While this is very pronounced for A325 bolts, it is less for alloy steel bolts. The 1-in. alloy steel bolts show trends much like the 7/8 in. bolts. Increased nut rotation to failure depends directly on the increased elongation capacity of bolts with greater thread length under nut. The more the bolt stretches, the greater is the nut rotation that must be applied to cause bolt failures.

The reduced ultimate load for these bolts in torqued tension and the high ratio of proof load to specified ultimate load (0.80) for the A354 BD and A490 bolts make it advisable to consider a minimum preload for installation somewhat below proof load. It is possible that the ultimate load in torqued tension could be less than 80% of that in direct tension, below proof load for minimum strength bolts.

3.4 COMBINED TORQUED-DIRECT TENSION TESTS

Figure 13 displays the results of this study. 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 curve then quickly approaches the direct tension curve for the same lot of bolts, shown as a dashed line. The curve showing 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

Figure 14 illustrates the relationship between load and elongation for repetitive torquing to 1/2 turn-of-nut of an A354 BC bolt with a thread length under the nut of 11/16 in. The dashed curve shows the corresponding torqued tension calibration. Twelve A354 BC bolts and 12 A490 bolts were tested by repeatedly tightening and then loosening the nut. Nine A354 BC and 6 A490 bolts were tightened with cycles of 3/4 turn-of-nut. Three A354 BC and 3 A490 bolts were tightened with 1/2 turn cycles and 3 A490 bolts were tightened with 2/3 turn cycles. In all cases the load at the end of each successive cycle was lower than for the previous cycle. No more than three cycles of installation were completed before failure for the bolts tightened to 3/4 turn-of-nut, while the lot tightened to 1/2 turn withstood an average of four cycles before failure. For every bolt tested the installation time for the second cycle was nearly triple that of the first. Because of the incremental nature of testing, this increase in time was not measured precisely or recorded.

These bolts were more sensitive to repeated applications of load than A325 bolts[1]. This severity is the result of greater cumulative thread damage caused by high loads and high stress concentrations acting on threads of the same geometry as the threads on the A325 bolts. The behavior of the A490 bolts seemed to be no more critical than that of the A354 BC bolts. However, a direct comparison is difficult because of the limited number of tests conducted.

3.6 BOLTS INSTALLED IN STEEL PLATE

Table 9 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 1/2 turn-of-nut, elongation after rupture, and nut rotation to failure. Also listed is the computed load at 1/2 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 1/2 turn for bolts tested under torqued tension in the bolt calibrator.

The most striking result indicated in the table is that the elongation at 1/2 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 7). This results in an increase in the load at 1/2 turn above that found in the bolt calibrator. Apparently 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. In the last two columns of this table are shown the nut rotations to failure for these tests and those listed in Table 7 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. 15 and 16 for the ED lot of A354 BD bolts torqued in 4-4 x 4 x 1 in. plies of A440 steel. At the top of Fig. 15 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.

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. 15. 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. 15 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 this manner, 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. 16. 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 1/4 turn-of-nut. The load-rotation curve obtained in the bolt calibrator is also compared with the ideal and solid plate curves in Fig. 16. 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 1/2 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 1/2 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 as is evident in Table 3.

2. The elastic behavior of high strength bolts in direct and torqued tension can be predicted using the simple theory for deformation of axially loaded members (Table 6).

3. All bolts had lower ultimate loads when tested in torqued tension than in direct tension. Ultimate loads of bolts torqued with shipping oil as the only lubricant varied from 78 to 92% of those tested in direct tension, with an average value of about 85%. Heavy lubrication resulted in slightly increased torqued ultimate loads for the A354 BD and A490 bolts with short lengths of thread under the nut (Fig. 6).

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 1/2 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 1/2 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 1/4 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 higher ultimate strength in torqued tension for the A354 BD and A490 bolts with short thread lengths under nut, heavy thread lubrication had little apparent effect. 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 lubricant.

9. Nut rotations from snug were found to vary from one to

nearly 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.

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 specifying an installed preload less than the proof load for alloy steel bolts.

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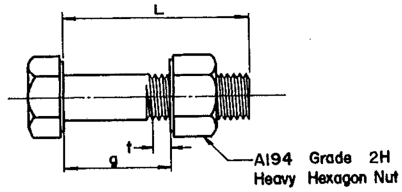
TABLE 1

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

SPECIFIED PHYSICAL PROPERTIES

Bolt Diameter, inches	Stress Area, sq. in.	ASTM Designation	Coupon Properties			Bolt Properties			
			Tensile Strength, min, ksi	% Elong. in 2 inches min.	% Red. of area min.	Proof Load, min, kips	Tensile* Strength min, kips	Hardness, Rockwell C	Hardness, Brinell
7/8	0.462	A325	-	-	-	36.05	53.15	22-34	235-321
"	"	A354BC	125	16	50	48.50	57.75	25-34	255-321
"	"	A354BD	150	14	35	55.45	69.30	32-38	302-352
"	"	A490	150	14	35	55.45	69.30	32-38	302-352
1	0.606	A325	-	-	-	47.25	69.70	22-34	235-321
"	"	A354BC	125	16	50	63.65	75.75	25-34	255-321
"	"	A354BD	150	14	35	72.70	90.90	32-38	302-352
"	"	A490	150	14	35	72.70	90.90	32-38	302-352

*Specified for bolts tested with 6 full threads under the nut, according to ASTM Designation A370, Supplement III

Table 3

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 4

COMPARISON OF BOLTS TO ASTM SPECIFICATIONS

Bolt Lot	ASTM Designation	Hardness, Rockwell C	Hardness, Brinell	Tensile Strength*		
				Number 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	277	3	62.3	108
DC-8-16S	"	32	288	3	83.1	110
AD-7-9S	A490	34	329	3	76.5	110
BD-8-11S	"	35	328	3	100.0	110
CD-7-9L	"	35	328	3	74.5	108
DD-8-11L	"	34	304	3	96.7	106
ED-7-12S	A354BD	38	338	3	77.8	112
FD-8-16S	"	37	331	3	99.3	109
GD-7-12L	"	32	331	3	75.5	109
HD-8-16L	"	36	332	3	100.5	110
LI-7-9S	A490	34	318	5	72.1	104
AB-7-9L	"	34	307	5	70.8	102
KK	"	35	323	-	72.3+	104
JJ	"	35	323	-	-	-

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

+From mill report

TABLE 5

DIRECT TENSION TEST RESULTS

Bolt Lot	ASTM Designation	Number of Specimens Tested	Ultimate Load			Rupture Load kips	Elongation, inches		
			Mean kips	Std. Dev. kips	% ASTM Minimum		At Proof Load	At Ult. Load	After Rupture
AC-7-2S	A354BC	3	72.6	1.88	126	64.3	.0114	.0854	0.173
AC-7-9S	"	3	65.0	1.57	113	52.0	.0136	.0758	0.190
BC-8-2S	"	3	91.0	2.26	120	76.3	.0115	.0783	0.140
BC-8-11S	"	3	82.9	1.60	109	61.7	.0139	.0919	0.263
CC-7-12S	"	3	62.3	0.20	108	48.7	.0139	.0900	0.300
DC-8-16S	"	3	83.1	1.22	110	64.0	.0141	.1079	0.293
AD-7-2S	A490	3	83.1	2.63	120	78.3	.0134	.0459	0.083
AD-7-9S	"	3	76.5	1.51	110	68.7	.0156	.0605	0.113
BD-8-2S	"	3	102.1	1.83	112	92.0	.0138	.0611	0.127
BD-8-11S	"	3	100.0	0.20	110	92.3	.0161	.0747	0.143
CD-7-2L	"	3	82.6	1.25	119	79.2	.0256	.0702	0.120
CD-7-9L	"	3	74.5	0.44	108	69.8	.0281	.0807	0.120
DD-8-2L	"	3	105.4	0.71	116	93.3	.0258	.0841	0.147
DD-8-11L	"	3	96.7	0.53	106	85.3	.0277	.0909	0.173
ED-7-12S	A354BD	3	77.8	0.67	112	71.7	.0159	.0619	0.120
FD-8-16S	"	3	99.3	2.18	109	81.3	.0169	.0899	0.207
GD-7-12L	"	3	75.5	0.82	109	71.0	.0275	.0839	0.137
HD-8-16L	"	3	100.5	1.25	110	91.7	.0280	.0938	0.137
LI-7-2S	A490	5	76.0	0.54	110	67.0	.0150	.0510	0.137
LI-7-9S	"	5	72.1	0.17	104	59.0	.0170	.0650	0.245
AB-7-2L	"	5	73.2	1.59	106	65.0	.0280	.0779	0.120
AB-7-9L	"	5	70.8	1.69	102	61.0	.0290	.0846	0.180
KK-7-2S	"	5	77.9	0.44	112	69.3	.0156	.0607	0.115
JJ-8-6S	"	5	99.2	1.57	109	85.0	.0160	.0625	0.189

TABLE 6

THEORETICAL ELASTIC BEHAVIOR

Bolt Lot	Proof Load kips	Calc. Elong. at Proof Load inches	Elong. at Proof Load/Calc. Elong.		
			Direct Tension	Torq. Ten. threads as received	Torq. Ten. threads lubr.
AC-7-2S	48.5	.0115	0.99	1.06	1.05
AC-7-9S	"	.0130	1.05	1.27	1.31
BC-8-2S	63.65	.0112	1.03	0.98	1.12
BC-8-11S	"	.0131	1.06	1.15	1.22
CC-7-12S	48.5	.0138	1.01	1.23	1.30
DC-8-16S	63.65	.0142	0.99	1.06	1.09
AD-7-2S	55.45	.0132	1.02	1.11	1.02
AD-7-9S	"	.0150	1.04	1.10	1.30
BD-8-2S	72.70	.0127	1.09	1.10	1.10
BD-8-11S	"	.0150	1.08	1.10	1.20
CD-7-2L	55.45	.0257	1.00	1.05	1.05
CD-7-9L	"	.0275	1.02	1.04	1.05
DD-8-2L	72.70	.0252	1.02	1.03	1.01
DD-8-11L	"	.0275	1.01	1.02	1.02
ED-7-12S	55.45	.0157	1.01	1.07	0.99
FD-8-16S	72.70	.0162	1.04	1.08	1.36
GD-7-12L	55.45	.0275	1.00	0.96	0.98
HD-8-16L	72.70	.0273	1.03	0.99	1.03
LI-7-2S	55.45	.0148	1.01	1.08	-
LI-7-9S	"	.0165	1.03	1.09	-
AB-7-2L	"	.0276	1.01	1.01	-
AB-7-9L	"	.0295	0.98	1.05	-
KK-7-2S	"	.0150	1.04	1.16	-
JJ-8-6S	72.70	.0153	1.05	1.03	-

TABLE 7

TORQUED TENSION TEST RESULTS

Threads as Received

Bolt Lot	Proof Load kips	Number of Specimens Tested	Load at 1/2 turn kips	Load at 5/8 turn kips	Ultimate Load: Mean, kips	Ultimate Load: Std. Dev. kips	Ultimate Load: % Direct Tension Ultimate	Rupture Load, kips	Elongation, inches: At Proof Load	Elongation, inches: At 1/2 Turn	Elongation, inches: At 5/8 Turn	Elongation, inches: At Ult. Load	Elongation, inches: After Rupture	Nut Rotation to Rupture revs.
AC-7-2S	48.50	3	49.1	57.6	61.3	1.36	84.5	47.0	.0122	.0128	.0210	.0512	0.113	1-1/2
AC-7-9S	"	3	52.8	55.1	56.5	0.87	87	36.7	.0165	.0260	.0369	.0614	0.167	1-3/4
BC-8-2S	63.65	3	75.3	77.8	78.5	3.50	86.5	43.3	.0110	.0202	.0308	.0389	0.110	1-1/4
BC-8-11S	"	3	70.2	72.2	72.7	4.49	88	55.3	.0150	.0291	.0304	.0473	0.110	1-1/4
CC-7-12S	48.50	3	51.1	53.6	55.7	0.30	89.5	40.3	.0170	.0227	.0345	.0669	0.160	1-7/8
DC-8-16S	63.65	3	70.8	73.5	74.5	1.50	90	49.7	.0150	.0299	.0430	.0562	0.170	1-3/4
AD-7-2S	55.45	3	48.9	62.8	70.5	1.82	85	58.0	.0147	.0127	.0185	.0376	0.080	1-1/4
AD-7-9S	"	3	60.9	64.8	66.9	2.11	87.5	53.0	.0165	.0209	.0313	.0510	0.120	1-3/8
BD-8-2S	72.70	3	84.5	90.7	90.7	0.58	89	71.7	.0140	.0181	.0280	.0280	0.103	1
BD-8-11S	"	3	72.5	80.5	83.0	7.86	83	58.0	.0165	.0173	.0273	.0441	0.120	1-3/8
CD-7-2L	55.45	3	45.7	50.1	71.9	1.86	87	66.7	.0270	.0219	.0244	.0652	0.110	1-3/8
CD-7-9L	"	4	46.9	55.7	62.6	2.06	84	56.2	.0285	.0240	.0316	.0610	0.105	1-1/4
DD-8-2L	72.70	3	64.0	80.0	90.3	1.15	85.5	70.7	.0260	.0223	.0289	.0498	0.107	1-1/4
DD-8-11L	"	3	67.0	78.8	84.0	2.65	87	59.7	.0280	.0262	.0345	.0537	0.147	1-5/8
ED-7-12S	55.45	4	59.2	64.0	67.6	1.95	87	52.8	.0168	.0183	.0279	.0484	0.145	1-3/8
FD-8-16S	72.70	3	77.8	83.8	88.2	2.36	89	68.8	.0175	.0222	.0298	.0541	0.143	1-3/8
GD-7-12L	55.45	3	32.7	42.6	69.3	0.87	92	58.0	.0265	.0155	.0206	.0725	0.127	1-3/4
HD-8-16L	72.70	3	66.7	81.5	91.2	1.44	91	75.3	.0270	.0250	.0336	.0616	0.173	1-3/4
LI-7-2S*	55.45	5	53.4	59.9	61.1	2.80	80.5	40	.0160	.0162	.0216	.0260	0.075	1-1/4
LI-7-9S*	"	5	50.0	55.4	58.4	3.00	81	34	.0180	.0156	.0206	.0310	0.110	1-5/8
AB-7-2L*	"	6	48.6	57.5	65.4	2.80	89	52	.0280	.0235	.0291	.0530	0.080	1-3/8
AB-7-9L*	"	5	41.1	50.8	61.8	2.18	87	50	.0310	.0219	.0268	.0700	0.114	1-3/4
KK-7-2S	"	10	56.2	60.2	60.4	3.50	77.7	47.5	.0173	.0182	.0276	.0295	0.062	1
JJ-8-6S*	72.70	5	81.0	85.8	87.3	1.26	87.9	64	.0158	.0201	.0311	.0466	0.145	1-1/2

*Snug load was taken as 10 kips for these lots

Table 8

TORQUED TENSION TEST RESULTS

Threads Lubricated

Bolt Lot	Proof Load, kips	Number of Specimens Tested	Load at 1/2 turn kips	Ultimate Load			Rupture Load kips	Elongation, inches				Nut Rotation to Rupture revs.
				Mean, kips	Std. Dev. kips	% Direct Tension Ult.		At Proof Load	At 1/2 Turn	At Ult. Load	After Rupture	
AC-7-2S	48.50	3	51.5	62.5	1.13	86	44.3	.0121	.0130	.0555	0.117	1-5/8
AC-7-9S	"	3	52.0	56.8	0.50	87.5	40.3	.0170	.0225	.0583	0.157	1-3/4
BC-8-2S	63.65	3	74.2	76.5	1.80	84	52.0	.0125	.0208	.0371	0.103	1-1/4
BC-8-11S	"	3	67.2	71.5	3.00	86.5	51.3	.0160	.0220	.0518	0.133	1-1/2
CC-7-12S	48.50	3	50.8	55.2	0.53	89	43.0	.0180	.0231	.0628	0.160	1-7/8
DC-8-16S	63.65	3	70.2	73.7	3.34	89	54.7	.0155	.0243	.0608	0.153	1-3/4
AD-7-2S	55.45	3	60.3	78.6	1.46	94.5	59.3	.0135	.0152	.0496	0.127	1-1/2
AD-7-9S	"	3	58.0	65.8	6.25	86	50.3	.0195	.0199	.0537	0.150	1-5/8
BD-8-2S	72.70	3	83.5	91.3	7.37	89.5	73.7	.0140	.0178	.0367	0.100	1-1/8
BD-8-11S	"	3	68.0	78.8	5.80	79	60.3	.0180	.0170	.0401	0.117	1-3/8
CD-7-2L	55.45	3	47.8	76.1	0.93	92	58.0	.0270	.0228	.0627	0.143	1-3/4
CD-7-9L	"	3	46.7	66.6	0.82	89.5	56.3	.0290	.0239	.0630	0.133	1-1/2
DD-8-2L	72.70	3	58.3	99.0	2.78	94	77.0	.0255	.0201	.0603	0.115	1-5/8
DD-8-11L	"	3	69.7	85.0	3.28	88	58.7	.0280	.0269	.0684	0.153	1-3/4
ED-7-12S	55.45	3	61.9	68.5	0.45	88	58.0	.0155	.0192	.0489	0.137	1-1/2
FD-8-16S	72.70	3	61.3	85.5	8.26	86	66.3	.0220	.0164	.0611	0.180	1-7/8
GD-7-12L	55.45	3	36.1	68.1	0.70	90.5	60.3	.0270	.0163	.0651	0.107	1-5/8
HD-8-16L	72.70	3	61.7	90.3	2.08	90	68.0	.0280	.0236	.0869	0.170	1-7/8

TABLE 9

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 7	Elong. after Rupture, inches	Nut Rotation to Rupture, revs.	Nut Rotation to Rupture from Table 8
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

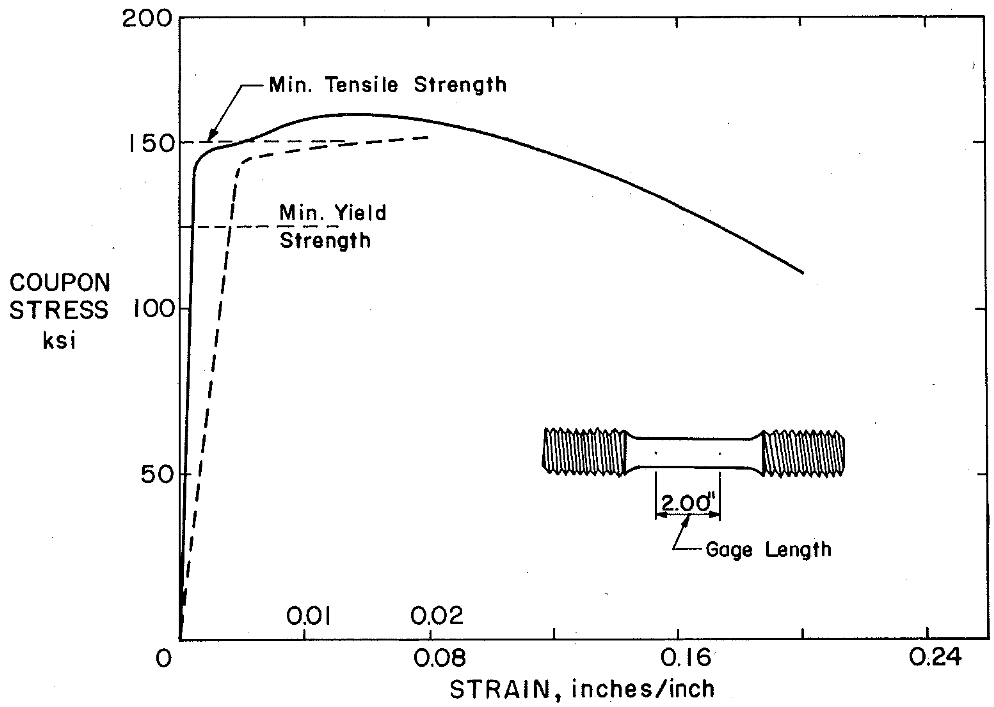


Fig. 1 Coupon Stress-Strain Relationship

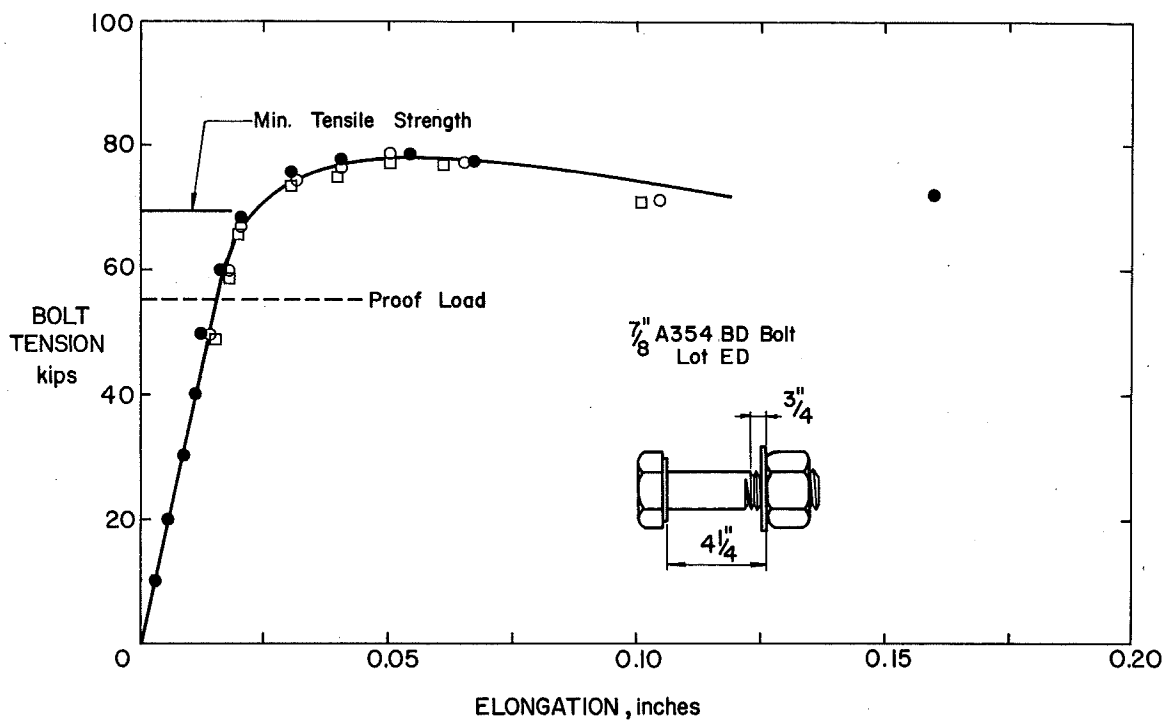
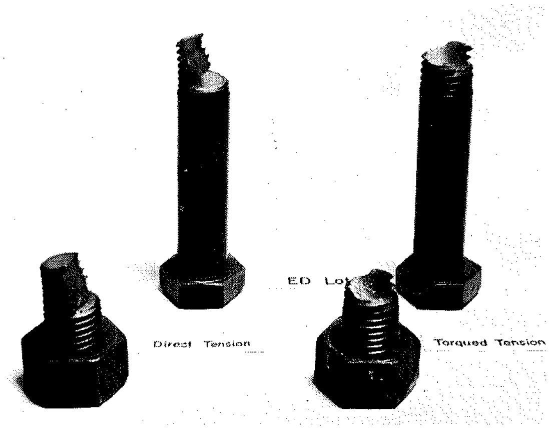
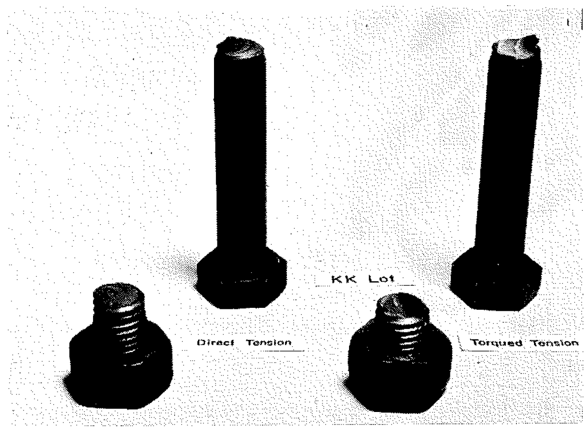


Fig. 2 Load-Elongation Relationship, Direct Tension



a) Long Threads



b) Short Threads

Fig. 3 Bolt Fractures

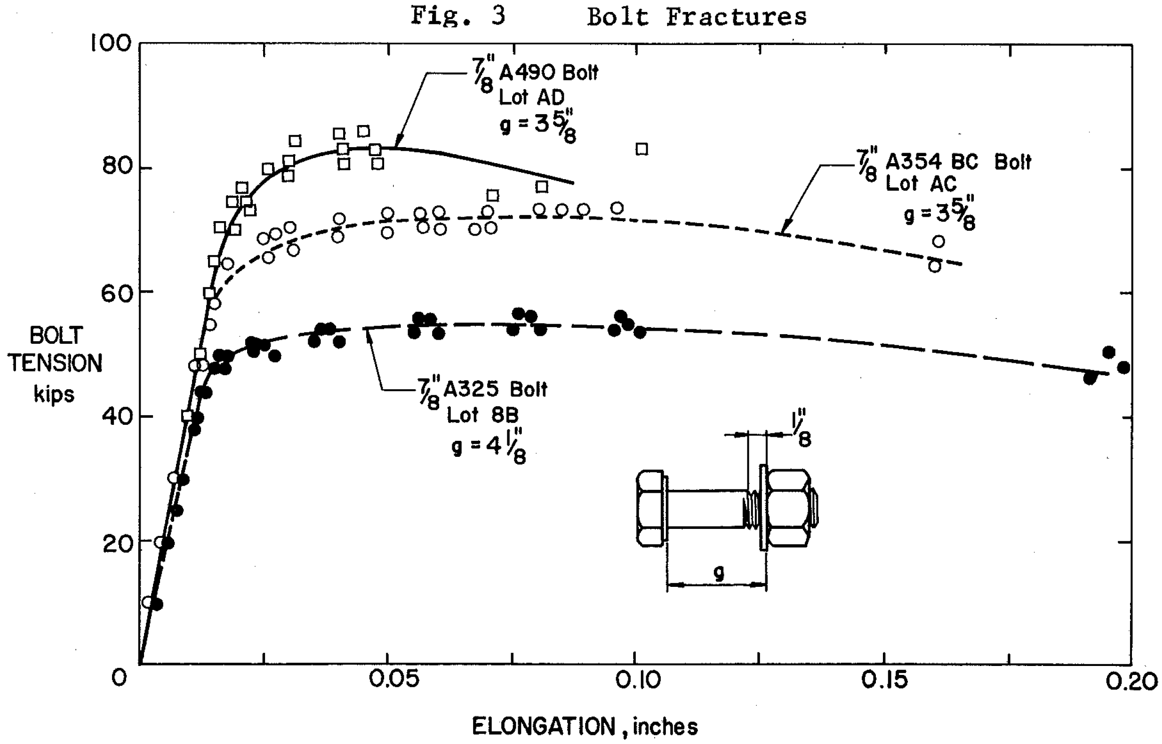


Fig. 4 Comparison of Bolt Types, Direct Tension

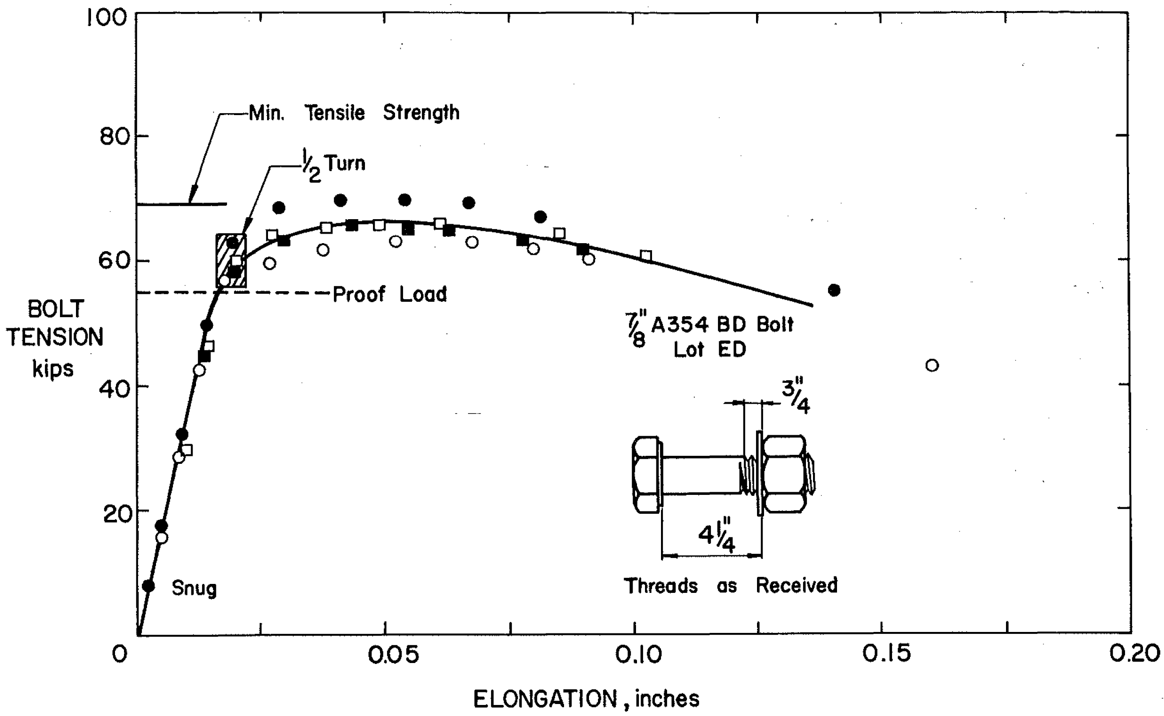


Fig. 5 Load-Elongation Relationship, Torqued Tension

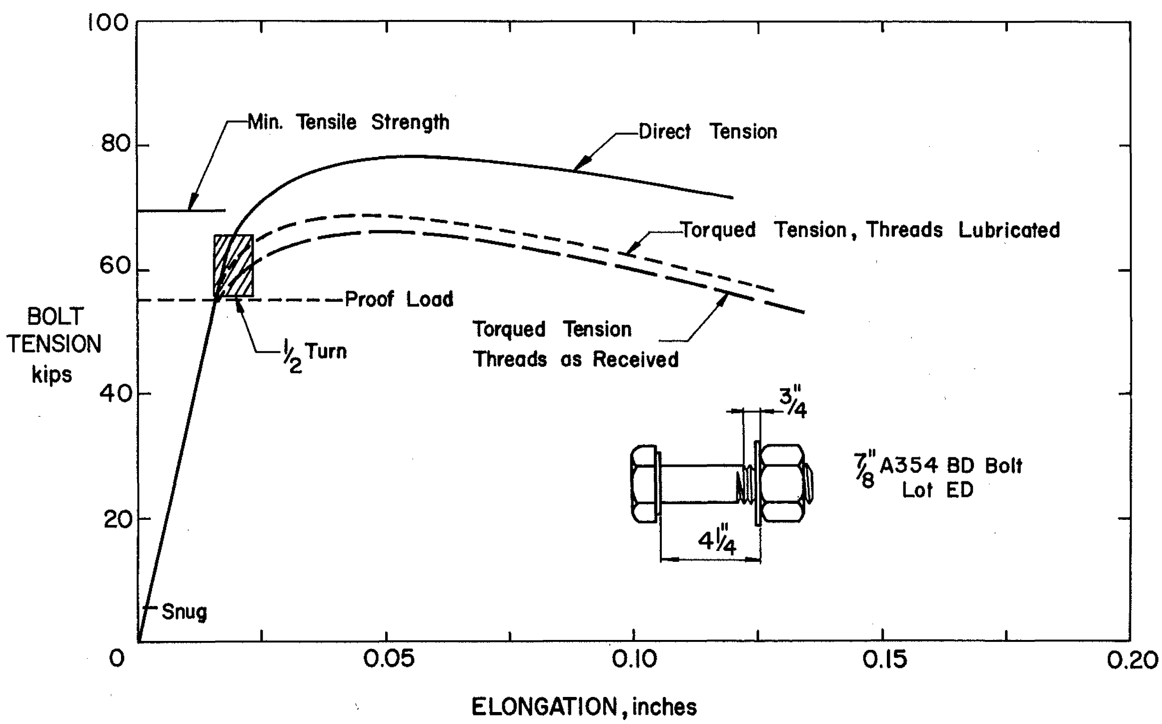


Fig. 6 Comparison of Loading Methods

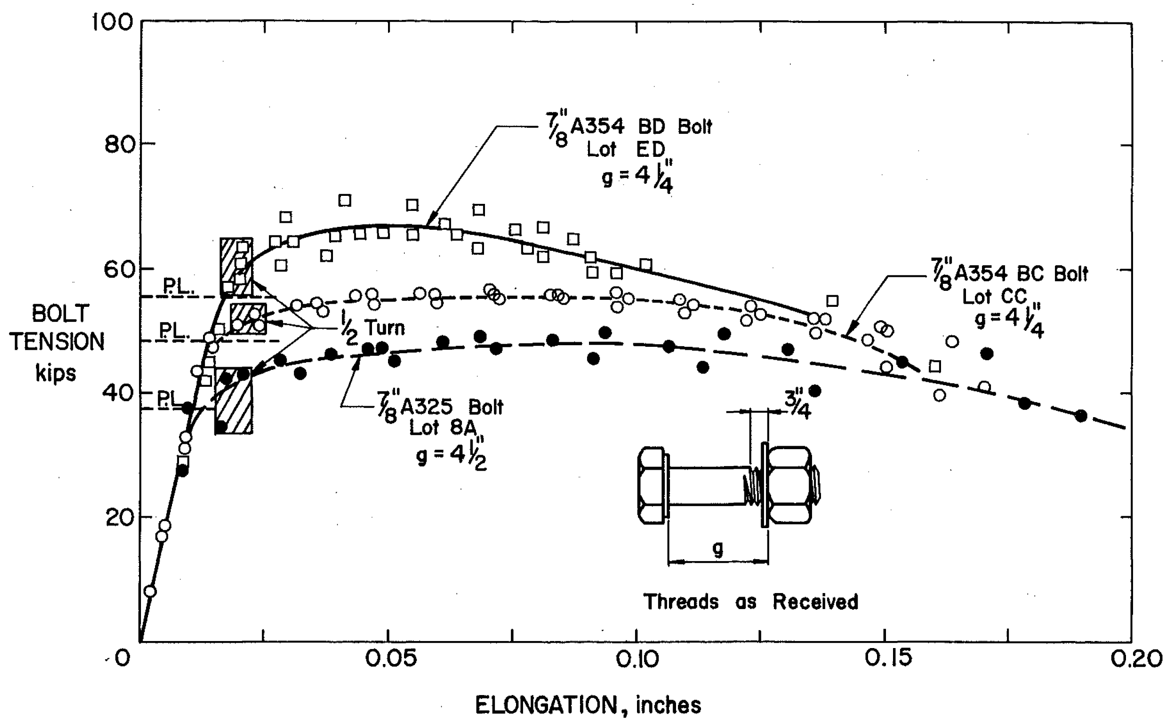


Fig. 7 Comparison of Bolt Types, Torqued Tension

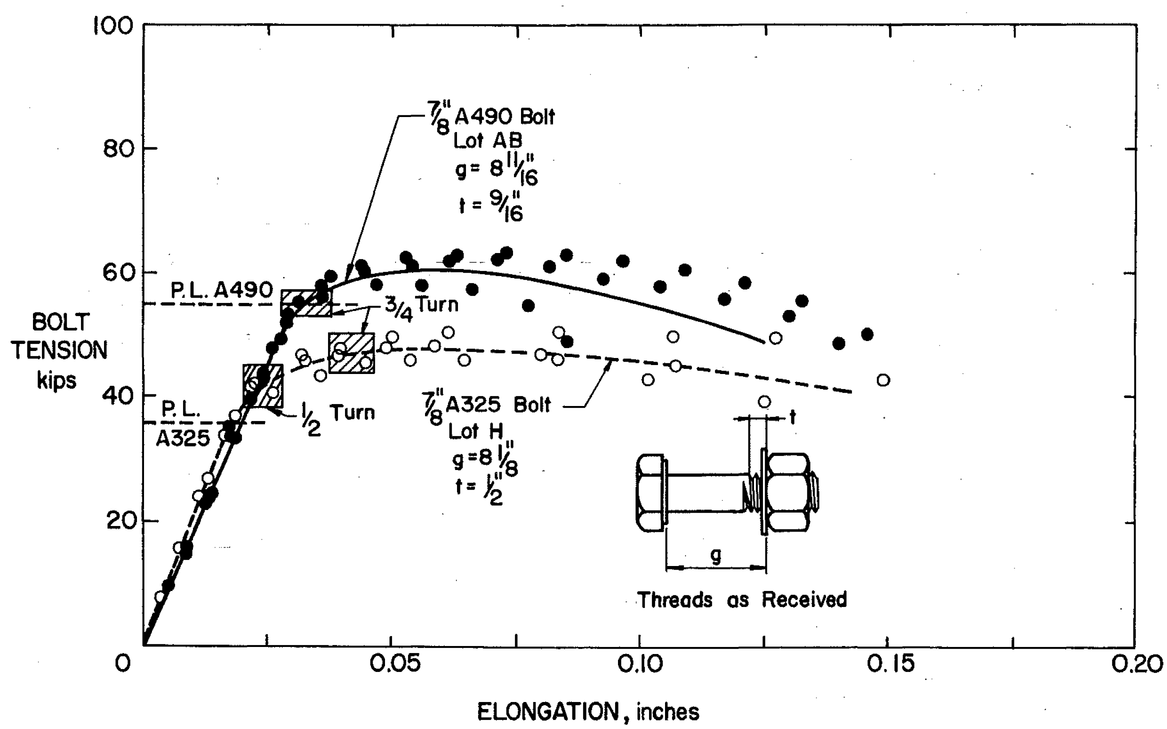


Fig. 8 Long Bolts, A325 vs. A490, Torqued Tension

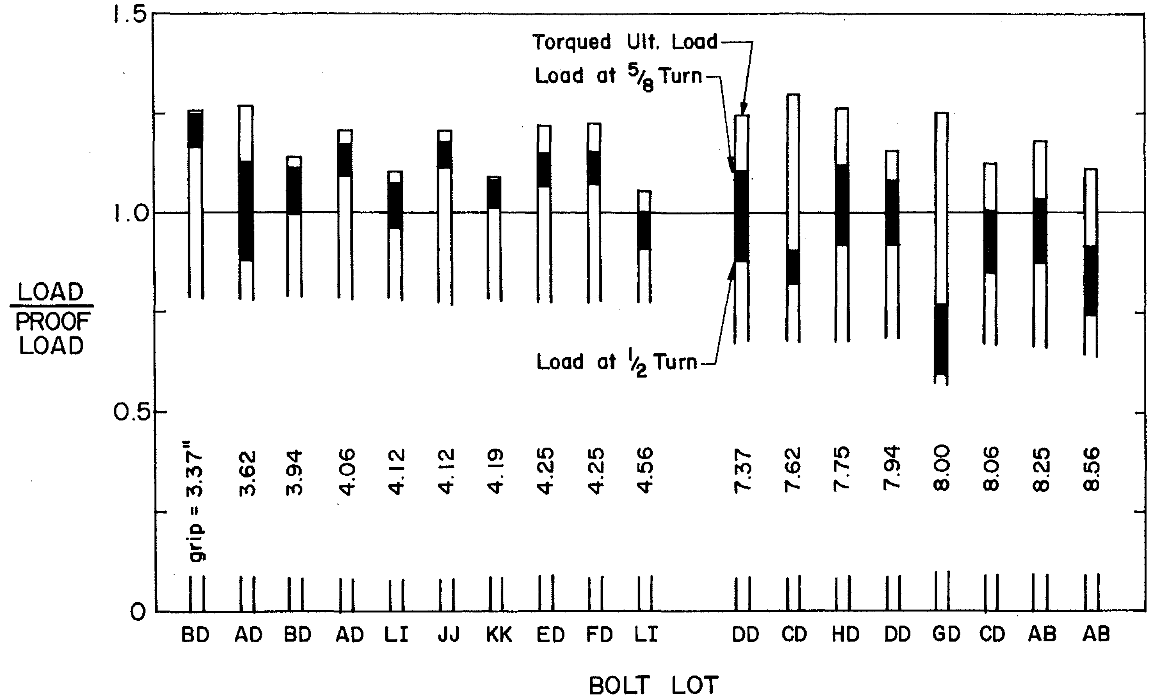


Fig. 9 Load at Specified Nut rotation

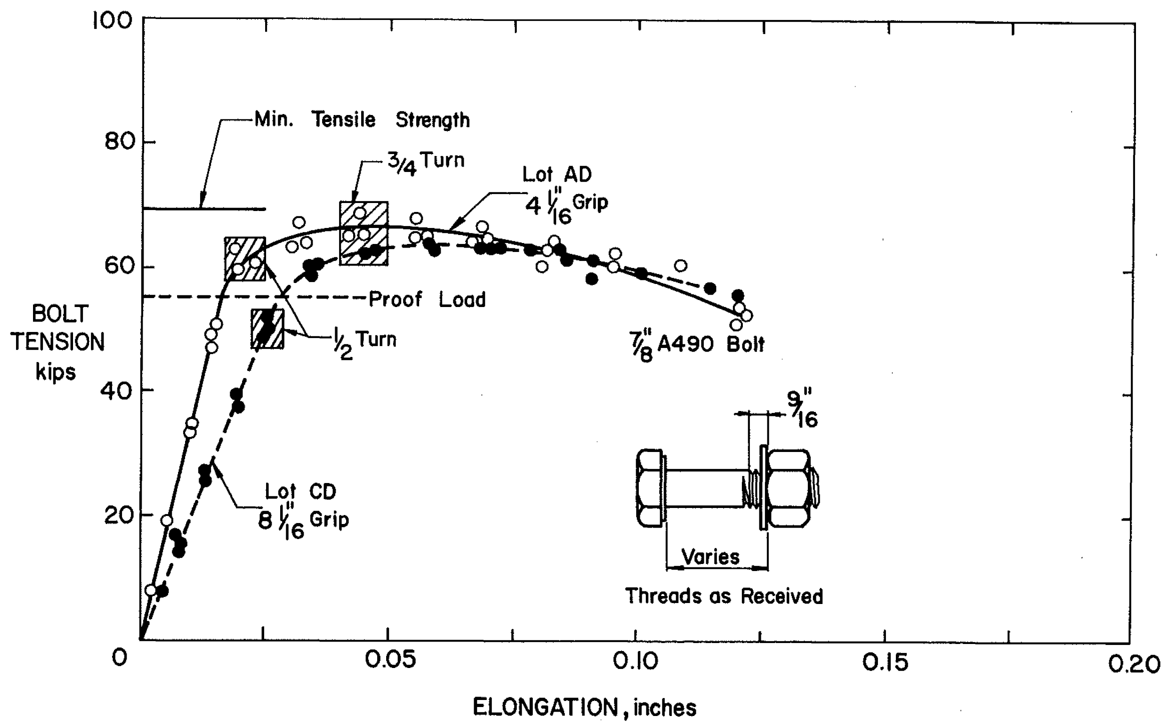


Fig. 10 Effect of Grip Length

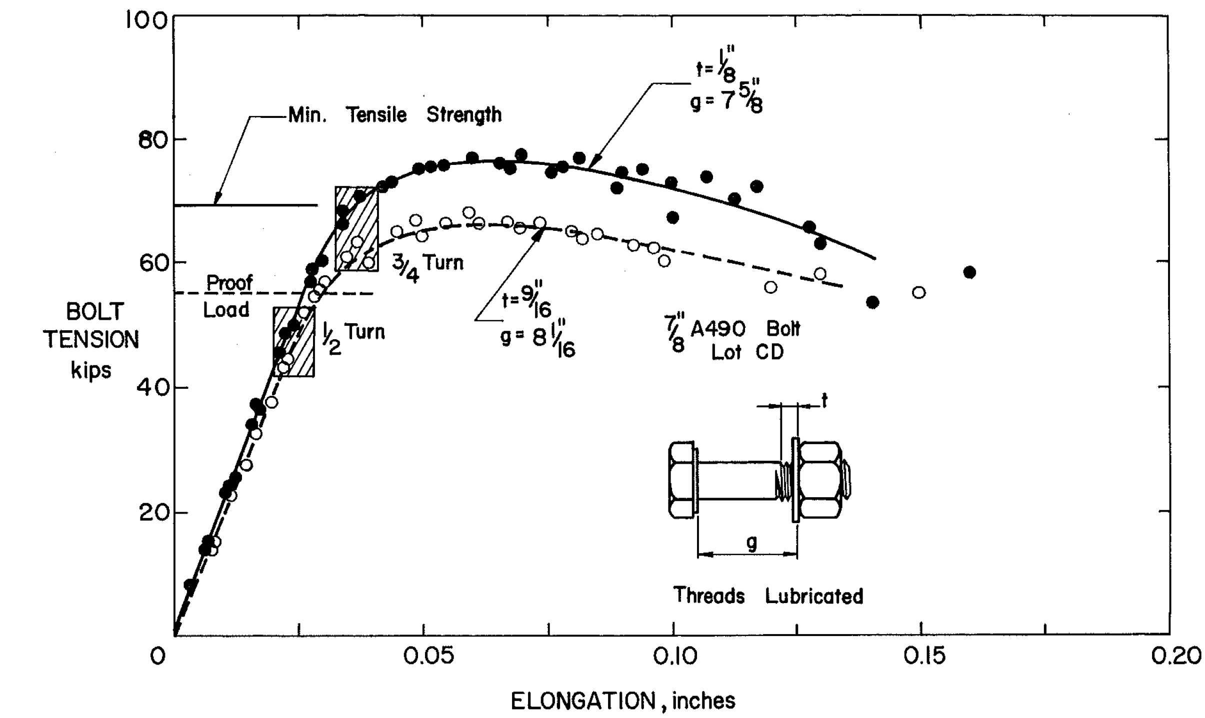


Fig. 11 Effect of Thread Length Under Nut, Torqued Tension

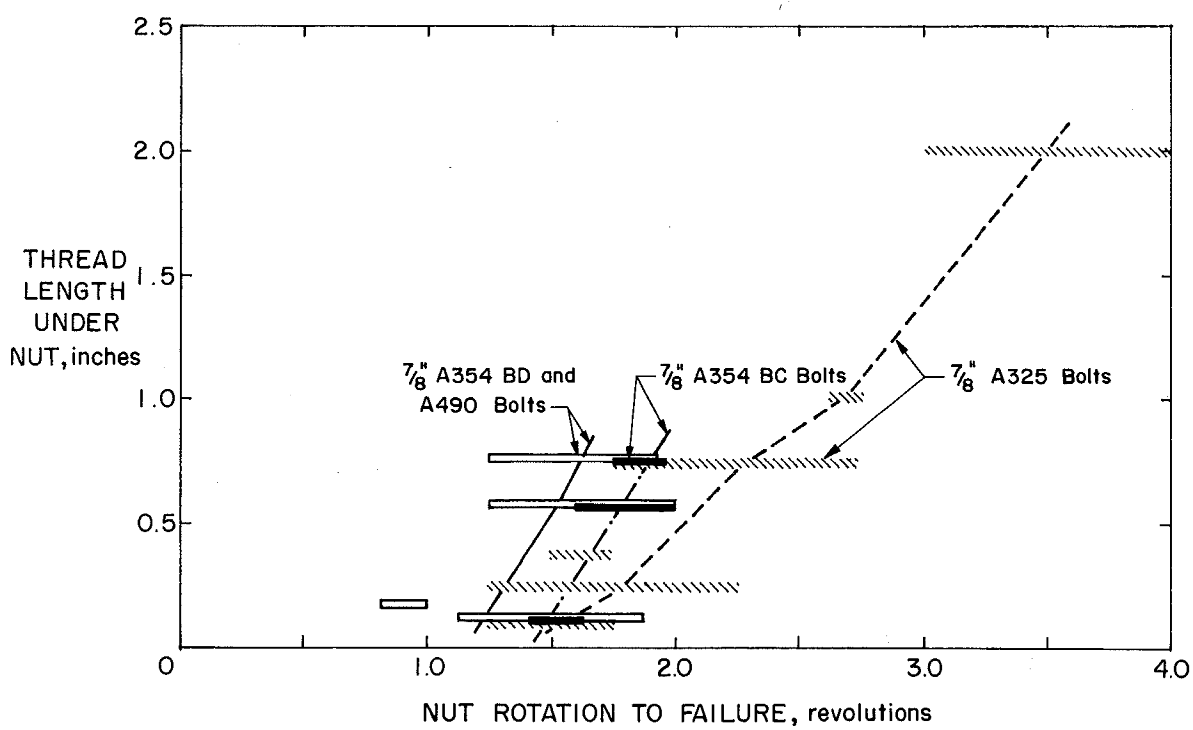


Fig. 12 Effect of Thread Length on Rotation Capacity

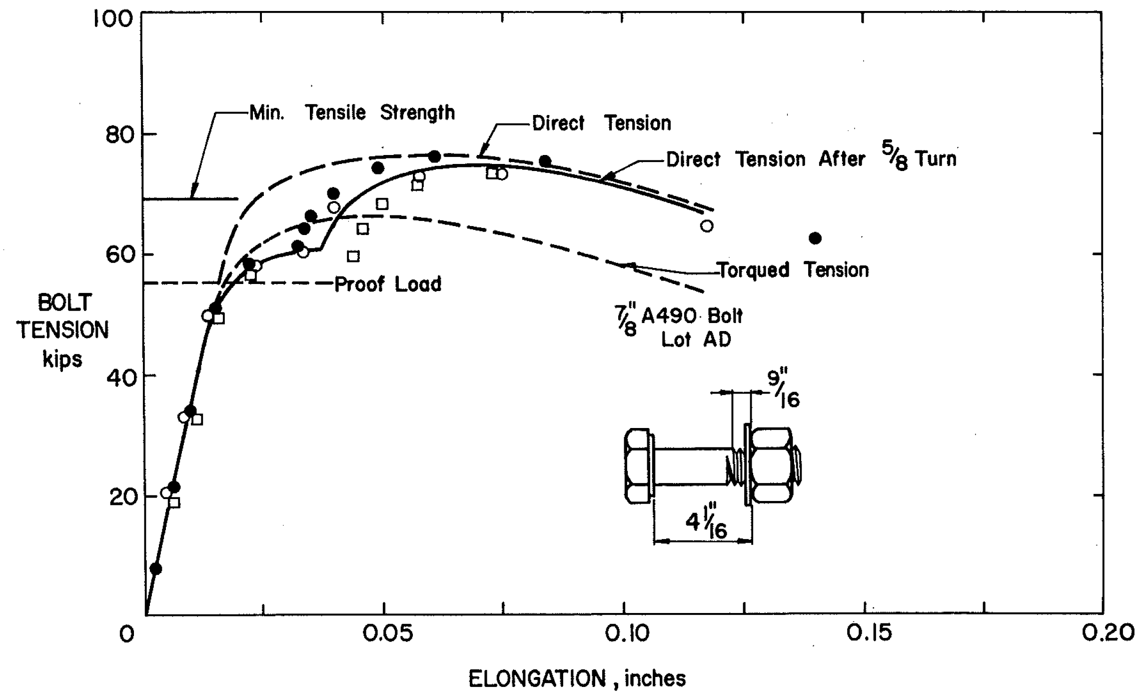


Fig. 13 Reserve Tensile Strength of Torqued Bolts

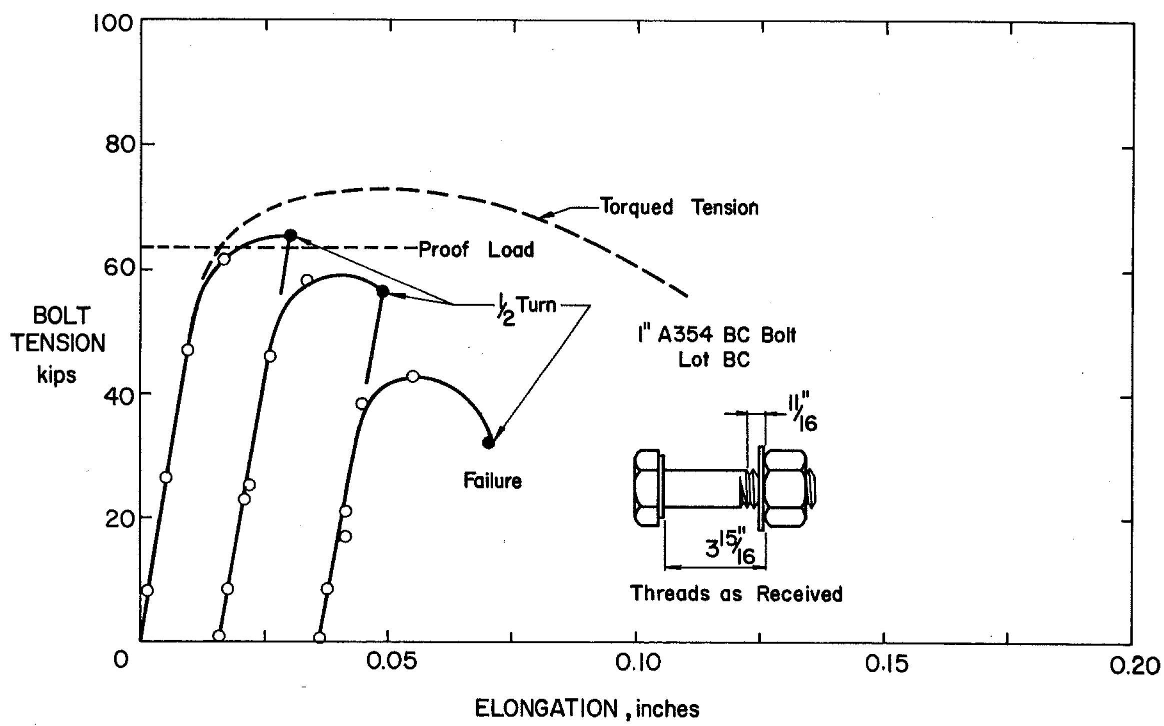


Fig. 14 Repeated Installation of Bolts, ½ Turn-Of-Nut

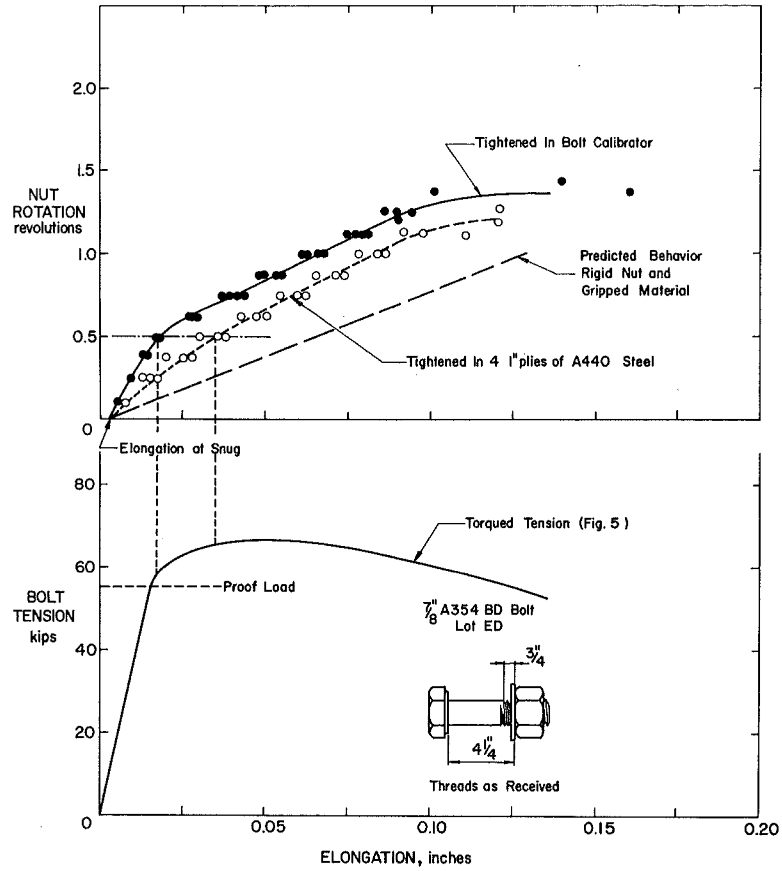


Fig. 15 Bolts Torqued in Steel Plates

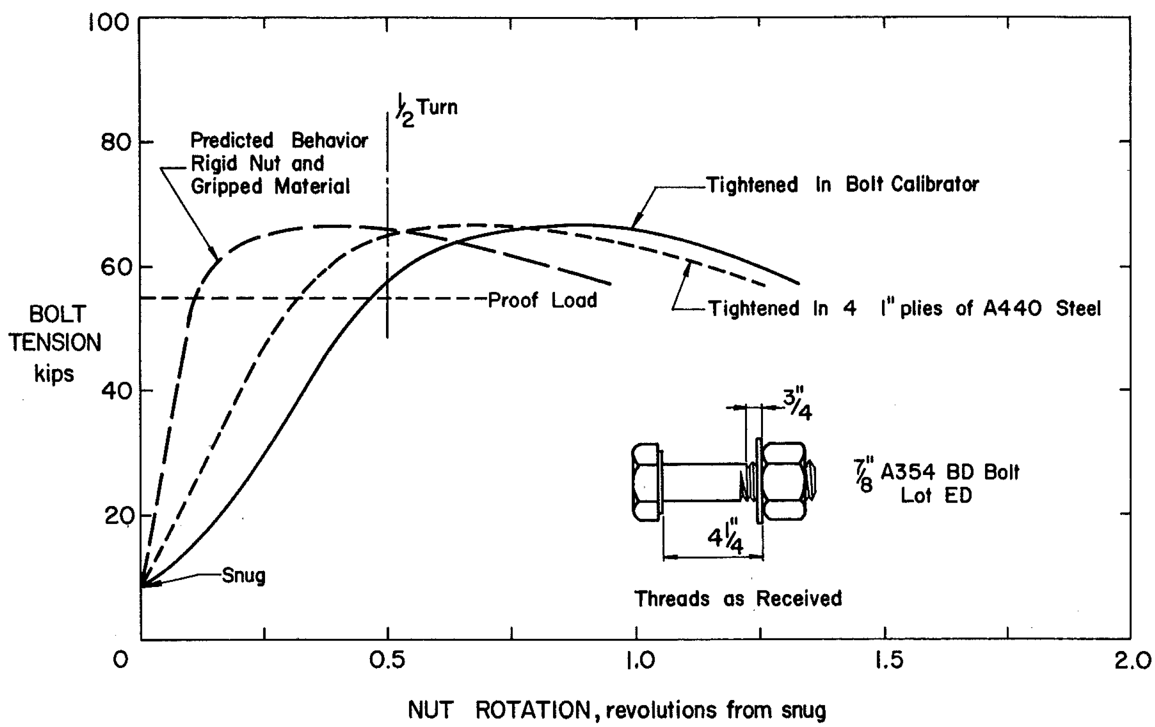


Fig. 16 Tension-Nut Rotation Relationships

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