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CALIBRATION AND INSTALLATION OF HIGH STRENGTH BOLTS

by

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SYNOPSIS

The need for accurate bolt calibration has come about as a result of the recent popularity of structural connections using high strength bolts. For the purposes of this report bolt calibration has been defined as the relating of internal bolt tension to some other readily observed quantity; e.g., bolt elongation, torque, or turn of the nut. Information contained in this report was compiled largely from control tests conducted at Lehigh University in connection with the Large Bolted Joints Project. All bolts used in these investigations were ASTM A-325. This report is intended to review available bolt calibration procedures, to discuss fully the procedure used at Lehigh, and to present information on the turn-of-nut method for installing high strength bolts.

I. INTRODUCTION

1.1 General

In structural joints connected with high strength bolts it is generally assumed that working loads are resisted by frictional forces acting on the faying surfaces of the connected material. These forces, in turn, are created by the internal tension induced in the bolt as the nut is tightened against the material. According to the classical theory of static friction, the value of these frictional forces depends on two things: the coefficient of static friction and the normal force. This normal force corresponds to the internal tension or "clamping" force of the individual bolts which go to make up a bolted connection.

When a bolt is tightened in an unloaded joint, it possesses a specific internal tension. As load is applied to the joint, however, this internal tension changes because of bolt deformation and because of changes in the grip length as the gripped material deforms under load. Thus, if one wishes to evaluate the slip characteristics of a bolted connection, he first must know the initial clamping force (T_i) exerted by each bolt in the pattern. Assuming that this information has been recorded, there still remains the problem of knowing the static coefficient of friction between the connected plies. One could, by experiment, evaluate a nominal coefficient of friction of a joint in single shear in the following manner.

$$\mu_{nom.} = K_{slip} = \frac{P_s}{\sum_{1}^{n} T_i} = \frac{P_s}{n \times \overline{T}_i}$$

In this expression P_s is the external load on the joint at slip; n is the number of bolts in the pattern; $\overline{T}_i$ is the weighted value of T_i, the initial clamping force.

If bolts are tightened into the elastic-plastic range where the tension-elongation curve is relatively flat, then:

$$\bar{T}_i \simeq T_{i(avg.)}$$

In this case, $T_{i(avg.)}$ is the value read from the tension-elongation curve by entering with $e_{avg.}$ and reading off the corresponding bolt tension. Therefore:

$$K_{slip} = \frac{P_s}{n \times T_{i(avg.)}} \qquad (1)$$

However, due to the change in internal tension as external load is applied to the joint, this coefficient of friction is by no means the exact coefficient. If the exact coefficient of friction is desired, one must know the history of the bolt tension so that the clamping force at the instant of slip is known. In this case,

$$\mu = \frac{P_s}{\sum_{1}^{n} T_s} \qquad (2)$$

where T_s is the bolt tension at the instant of slip. This cannot be simplified in the manner of Eq. (1) because, in bolted joints, some bolts relax more under external load than others, depending on their location in the joint.

It is evident then that there may be some variation in reporting coefficients of friction depending on when and how the internal tension measurements are made. Because of the difficulties in devising equipment that can record all bolt tensions during the life of a test joint, investigators have generally reported the coefficients based on the rather easily determined initial clamping force. Such coefficients have been called "apparent coefficient of friction", "nominal coefficient of friction", and "slip coefficient", in order to indicate their fictitious nature. The latter expression, slip coefficient, is probably the best one because the others, through shoddy usage, can easily be contracted to "coefficient of friction".

Having dismissed the question of when to measure bolt tension the question of how to measure it still remains.

1.2 Bolt Calibration Relationships

It is by means of a bolt calibration curve that the tension in bolts installed in structural joints can be estimated once the readily observed quantity is measured. There are a number of different quantities to which the internal tension may be related.

a) Internal Tension vs. Torque
b) Internal Tension vs. Elongation
c) Internal Tension vs. SR-4 Strain Gage Output
d) Internal Tension vs. Load Cell Output

Each method presents its own advantages and disadvantages.

Tension vs. Torque

Since turning the nut of a bolt against the resistance of the gripped material induces an internal tension in a bolt, one could use hand torque wrench readings as an indication of the tension in the bolt. As early as 1930, C. Batho and E. H. Bateman(1) conducted studies to determine the amount of torque required for a given factor of safety against slip. They concluded that the amount of torque required would increase as the cube of the diameter. They also reported that the bolt is more highly stressed during the tightening process than it is after the wrench has been taken off.

In 1954, Munse, Wright, and Newmark(2) offered a simple relationship for determining the amount of torque required to induce a given tension in a bolt.

$$\text{TORQUE} = \text{KPD}$$

D is the nominal bolt diameter; P is the bolt tension in pounds and corresponds to T_i of this report. K is a dimensionless factor which depends on the material and the condition of the surface of the threads, nuts, and washers. It may range from approximately 0.18 to 0.29 for bolts tested in the as-received condition. A fair approximation of the torque may be obtained by use of $K = 0.20$.

From a practical standpoint, this relationship between the torque indicator on a manual torque wrench and internal tension induced in a bolt is erratic and results in a wide spread of tension values. Other experimenters(3) point out that a torque criterion is not the most efficient way of guaranteeing the preload. Furthermore, the factor of safety against stressing the bolt to its ultimate load during the tightening operation is also quite small when a torque control is used. Nevertheless in the 1954 specification of the Research Council on Riveted and Bolted Structural Joints(4) a table of equivalent torques is listed as a guide to proper bolt tensions.

As other bolt calibration procedures are discussed, it will become evident that a torque criterion is best suited for inspection purposes even though it may not be the best method for control of original bolt tightening.

Tension vs. Elongation

A tension-elongation relationship has been used by many investigators. The method consists of stretching the bolt in some way and measuring the resulting change in length with an extensometer type measuring device. In 1954, Hechtman,(5) while investigating the slip of joints under static load calibrated each bolt used in the tests at its exact grip to obtain the relationship between directly applied bolt tension and elongation. At the University of Illinois, Petersen and Munse(6) used this elongation relationship in their tests on bolted connections.

With properly designed instruments, accurate elongation readings are not difficult to obtain. The extensometer must be capable of indicating changes of .0001" in order to be successful. As known loads are applied by a loading device, corresponding elongations can be recorded to ultimate load and beyond. This is quite a simple laboratory procedure.

In the field, however, it would not be feasible to measure the zero length of each bolt and, even more difficult, the final length of the installed bolt. Since the correct internal tension is a function of the change in length of a bolt, this tension-elongation relationship has no practical field application.

Tension vs. SR-4 Strain Gage Output

Another method for calibrating bolts is to mount SR-4 type strain gages on the bolt. As load is applied to the bolt by some means, the material strains are picked up by the gages. G. A. Maney(7) used this scheme mounting the gages diagonally on the bolt barrel to measure normal tensile and torsional shearing unit stress. He concluded that before a bolt is twisted off or the threads are stripped, the metal of the bolt is stressed in tension beyond the proportional limit. When the axial stretch of the threaded portion approaches its ultimate value, the threads of the elongated bolt no longer fit the threads of the nut and tremendous frictional resistance develops. This binding of the threads then causes either thread stripping or shear failure in the bolt.

In another article(8) Maney describes how SR-4 gages were mounted on lines 45 degrees to the bolt axis to produce readings of axial load in the bolt. The bolts were tightened with manual torque wrenches so that torque-tension relationships were finally obtained from the primary tension SR-4 gage output relationships. Once this latter relationship has been successfully established, any desired prestress can be placed in a bolt of the same lot by hand torquing or direct pulling until the required strain increment is attained.

Tension-elongation readings with SR-4 gages mounted 120 degrees apart on the bolt shank were checked by Petersen and Munse.(6) The lead wires were passed through small holes drilled in the head of each bolt. For bolts with strain gages they found it necessary to drill the holes in the connected material 3/16" larger than the nominal bolt diameter to accommodate the gages. These preliminary precautions do not affect laboratory work, but are impractical for erectors and fabricators. It should also be noted that the strains in the threaded portion within the grip area will be greater than those indicated by the output of SR-4 gages mounted on the shank of the bolt since the shank remains elastic throughout most of the loading of a bolt. Also, SR-4 type gages are limited since they are generally ineffective should the shank become inelastic.

In summary, then, this method of calibration is satisfactory for some laboratory work. It does not, however, use the gages as effectively as possible.

Tension vs. Load Cell Output

A load cell is a cylindrical piece of steel into which the bolt to be calibrated is inserted. SR-4 type gages are mounted on the outside of the load cell rather than on the bolt shank. R.L. Sanks(9) describes a load cell designed for use at the University of Utah. This cell was very satisfactory in overcoming errors of creep and lack of uniformity in materials and heat treatment. Similar load cells have been used at the University of Illinois. Four strain gage rosettes were located at 90 degrees around the outside shell. One disadvantage of the load cell is that separate load cells must be used for each bolt size. Also, if one tries to use a load cell on a bolt in a connection, the bolt must necessarily be longer than standard by the length of the load cell. On the other hand, its accuracy is very good.

After studying and considering each method of bolt calibration, it was agreed that the internal tension-elongation relationship best suited the calibration needs at Lehigh. The number of bolts to be calibrated was quite large in view of the over-all plans of the Large Bolted Joints Project which includes the use of bolts of numerous lengths and diameters. The need, therefore, was for a direct and simple procedure for accurate calibration. The testing equipment and instruments had to be long-range items which could dependably produce similar results over a period of years. Since the turn-of-nut procedure(10) was used in bolting up these joints, continuous readings during the tightening process were not necessary; therefore, the tension-elongation relationship was actually best suited for calibration and, subsequently, for determining changes in length and the resulting tension of each bolt in a large joint.

1.3 Methods of Inducing Tension

There are two ways of inducing tension in a bolt. Since the method of inducing the bolt tension has a marked effect on the tension-elongation relationship, these methods will be discussed.

To induce an internal tension in a bolt, it is necessary to stretch the bolt in some way. This can be accomplished by subjecting the bolt to a direct axial load (direct tension) or, more realistically, to cause the bolt to elongate by turning the nut against the resistance of gripped material (torqued). This latter method more closely simulates the actual field condition where the bolts are usually tightened with a pneumatic impact wrench. It has been reported previously that tensions induced by this method are ultimately lower than tensions induced by a direct axial pull on the bolt. H. O. Hill,(11) reports that when bolts (.15% to .24% carbon) were pulled to failure by tightening the nut, the ultimate strengths in tension were reduced to about 68% to 75% of their values in pure tension.

The direct tension method, on the other hand, is better suited for laboratory work. For this reason, the ASTM specification governing A 325 bolts stipulates the direct tension type of test. In summary, then, while torqued calibration best simulates actual conditions which would be encountered in bolts installed in the field, the direct tension method is best suited to laboratory and control testing. Both procedures have been investigated in the tests conducted at Lehigh.

1.4 Scope

Test results of the work carried out at Lehigh were complete to the point that the following observations were possible:

(1) The effects of torqued calibration and direct tension calibration procedures on the tension-elongation relationship were compared for three commonly used bolt sizes, 7/8", 1" and 1 1/8".

(2) From the torqued calibration data, results of torquing by 45 degree rotation increments were compared with the more realistic continuous torquing method. This particular comparison was designed to indicate whether it was necessary to obtain a complete curve to check tensions and elongations while also affording an opportunity to gather useful information on the turn-of-nut method.

(3) The advisability of re-using high strength bolts which had been previously installed in a connection according to the turn-of-nut procedure was also included in these observations.

(4) Finally, the effect of grip length as well as thread length in the grip area was indicated in the data collected in this study.

2. MATERIAL AND EQUIPMENT

2.1 Bolt Properties

All bolts used in the bolt calibration work at Lehigh were ASTM A-325 high strength bolts with quenched and tempered washers and heavy semi-finished hexagon nuts. The bolts were furnished by the Lebanon Plant of Bethlehem Steel Company and included 7/8", 1", 1 1/8" diameters. The bolts ranged in length from 5 1/2 inches to 8 1/2 inches under head and were tested at grips of 4", 4 3/4", 5 1/4", 6" and 6 3/4". Most test bolts had the standard length of thread; however, a few full threaded and other non-standard bolts were tested.

2.2 Preparation of Test Bolts

The first step in the preparation of test bolts consisted of identifying each bolt. A lot designation and a bolt number were stamped on the head and shank ends. In this manner each bolt of the lot was positively identified.

A second and most important preliminary operation was center drilling holes in the center of the head and shank ends to accommodate the points of the C-frame extensometer. The center drilling was done with a combined drill and countersink, type 217, so that the depth of the countersunk portion was between 1/32" and 1/16". No attempt was made to provide each bolt in a certain lot with a constant length under head since one need only be concerned with change in length to determine the elongation of a bolt. For each bolt, however, these center-drilled holes provided a constant point of contact with the extensometer tips thus removing a major source of error. The included angle of the countersunk portion of the center-drilled hole was greater than the included angle of the extensometer points. (Fig. 1) In this manner the point of contact between the bolt and the tips of the measuring device was the inside edges of the countersink and not the bottom of the hole. This provided a protected measuring surface which could not be damaged during the impact bolting procedure.

2.3 Description of Equipment Used

The equipment required to establish the internal tension-elongation relationship for both direct tension and torqued calibration is described briefly.

In the direct tension phase of this study, a 300^k hydraulic universal testing machine was used to induce the internal tension in the bolt. In order to use the testing machine special tension grips (Fig. 2) were needed. These were designed for loads up to 120^k with the center holes large enough for testing 1 1/8" bolts. Bushings shown in front of the grips were designed to modify this center hole to accommodate 1" and 7/8" diameter bolts with the usual clearance of 1/16".

The Skidmore-Wilhelm bolt calibrator(12) was used to measure internal tension in the torqued calibration series of tests. It is a commercial device manufactured by the Skidmore-Wilhelm Manufacturing Company and is commonly used to adjust impact wrenches at the erection site. In actual field procedure a bolt is inserted in the device, being held in place by changeable bushings and plates so that one machine can be used to adjust wrenches on a number of different bolt sizes. Tightening the nut transmits pressure through the hydraulic load cell to a calibrated gage indicating bolt tension in pounds. By observing this gage as a bolt is being torqued in the device, the operator can adjust the air pressure or torsion bar control so that the wrench stalls as the bolt is torqued to any desired tension.

When the turn-of-nut method is used to install bolts, however, the Skidmore-Wilhelm device is no longer necessary except for calibrating manual torque wrenches used for inspection purposes.

The particular device used had been modified so that bolts which had been torqued to various levels of prestress could be jacked statically to failure by a hydraulic pump connected to the pressure cell of the Skidmore-Wilhelm. Figure 3 shows the calibrator with the pressure hose leading from it to the hydraulic pump. Connections were designed so that this modification in no way impaired the operation of the device during standard operation.

In order to provide the necessary grips, solid thick washers were machined to "pack out" the Skidmore-Wilhelm. To accommodate the C-frame extensometer used to measure elongation (Fig. 4), the calibrator was used in the horizontal position which is contrary to usual field procedure. Accuracy of readings was insured by the calibration of the device in a 120^k testing machine before and after testing (Fig. 5). Testing machine load was plotted against Skidmore-Wilhelm load. From the resulting calibration curve it can be seen that the Skidmore-Wilhelm load was approximately 3 kips lower than the testing machine load at any point on the curve. The curve was established by continuous loading; points on it were substantiated by rapid loading to simulate what happens when the nut is tightened to one-half turn in approximately 6 seconds.

Figure 6 shows the extensometer used in the tests at Lehigh. Measurements were obtained from the dial gage which was capable of indicating changes in length of .0001". As stated previously, the tip of the dial plunger was made so that the point would not rest on the bottom of the center drilled holes. The pointed tip at the other end of the frame was threaded and provided with a knurled lock ring so that it could accommodate a minimum tip to tip length of 5 1/2" and a maximum length of 9 1/4". In addition, a counterweight was attached so that the instrument would balance in the vertical position when mounted on a bolt. In measuring initial and final lengths of bolts readings were considered acceptable when three consecutive trials agreed within .0002".

The impact wrenches used were Chicago Pneumatic 610 and Chicago Pneumatic 612. The larger wrench, capable of exerting more energy, was used to torque 1" and 1 1/8" bolts. Hypodermic pressure gages were used to check the air pressure in the line at the wrench.

3. DESCRIPTION OF TESTS

3.1 Direct Tension Calibration

Since all the bolt calibration work done at Lehigh has been in the form of control tests for the Large Bolted Joints Project, all bolts were tested with grip distances corresponding to those of the large joints. Single bolts were pulled in tension in a 300^k testing machine while elongations were read using the C-frame extensometer. Figure 7 is a typical view of a bolt as it was being tests.

The procedure for obtaining a direct tension vs. elongation curve was as follows: The bolt to be calibrated was selected and center drilled. It was then inserted in the special tension grips in the testing machine and the postion of the testing machine heads set so that at the required grip the nut was only finger tight and the bolt was unstressed. Zero readings of elongation were taken with no load on the bolt. Load was then applied to the specimen in five kip increments to the specification value of minimum elastic proof load. At this point load was removed in increments to zero. The bolt was then measured a second time at zero load to insure that the permanent elongation did not exceed the specification maximum of .0005 inches. Having checked the minimum elastic proof load requirement, testing was resumed in similar increments of load.

This method provides corresponding load and elongation readings all the way to rupture. However, as the curve becomes relatively flat, it is generally advisable to change from a load increment criterion to an elongation increment criterion. This precedure was used to establish the tension-elongation curve in Fig. 8. While load increments were used, the extensometer was left on the bolt, but when higher loads were reached, it was removed during loading and replaced after the load had been allowed to stabilize. When a desired elongation was reached the loading valve on the testing machine was closed. A slight drop in load was noticed after the valve was closed. This dropping of load was to be expected and can be attributed to leakage in the hydraulic system of the testing machine as well as to stress relaxation in the bolt.

3.2 Torqued Calibration

The primary objective of this series of tests was to establish tension-elongation relationships caused by turning the nut rather than by pulling the bolt in direct tension. Curves of tension vs. elongation were established for 7/8", 1" and 1 1/8" diameter bolts of various lots. Initial elongations were measured with the extensometer at a snugging load of 8^k on the bolt. This load was chosen to simulate the "snug" position of the turn-of-nut method. An initial load of 5^k was set on the Skidmore-Wilhelm gage, but the 3^k correction factor determined from the calibratinn curve of the Skidmore-Wilhelm caused the actual tension in the bolt to be 8^k. This relatively small amount of tension was induced with a spud wrench. Using an impact wrench, the nut was rotated in 45 degree increments. Load and elongation readings were recorded at each increment until failure occurred or until it was felt that failure was imminent. At this time the nut was removed and the final length of the bolt was measured.

Secondly, there was a question as to how a bolt which was elongated by continuous torquing would compare with the curve established by 45 degree increments of turn. An impact wrench was again used to continuously turn the nut a predetermined rotation increment. Rotation increments of 1/2 turn, 1 turn and 1 1/2 turn were chosen. This procedure also served the dual purpose of checking the effectiveness of the turn-of-nut method in achieving specified bolt tensions as well as comparing the uniformity of tensions in a number of bolts.

3.3 Re-use of High Strength Bolts

A third portion of the torque calibration program was designed to investigate the possibility of re-using high strength bolts which had been previously tightened according to the turn-of-nut method. First, a 7/8" diameter bolt was torqued in 45 degree increments of rotation from a snugging load (T_S) of 8^k. Load and elongation readings were taken at each increment and represent one point on the graph. After being tightened one-half turn from the snug position, the rotation of the nut was reversed and load removed to simulate the removal of a used bolt. After all load had been removed, the snugging load was re-applied and the nut was once more rotated through one-half turn. In this manner, the same bolt was torqued to one-half turn from the snug position a total of seven times whereupon rotation was continued to failure. Load and elongation readings were recorded through out the entire test furnishing a complete test history.

This same general procedure was used to test two more bolts from the same lot except that, in these tests, one complete turn of nut was used rather than one-half. The first of these two bolts was torqued to one full turn only once while, for the second, the load-unload sequence was repeated until rupture occurred. Again, a complete history of each test was recorded.

4. TEST RESULTS

4.1 General

A total of 110 bolts were calibrated. These represent 13 different lots and three different diameters. The greatest portion of the work was conducted with 7/8" bolts. Most of the bolts were close to the minimum strength specified by ASTM-A 325. Bolts of the Q-W lots inclusive were actually from the same lot insofar as steel and heat treatment were concerned, but they were given different letter designations because of the different lengths of bolt and of thread. The Q-W bolts had cut threads while all other bolts had the standard rolled thread.

4.2 Direct Tension Calibration

Since three sizes of bolts, 7/8", 1" and 1 1/8", were tested in each phase of the direct tension tests, a portion of this discussion will be devoted to each particular size. Figure 9 is a table showing the results of the entire bolt calibration study and will serve as a reference for this entire discussion.

Bolts from ten different lots of 7/8" bolts were tested in direct tension. Figure 10 shows the average tension-elongation curve for five of the B-lot of bolts along with average curves for the A-lot and G-lot. It is clearly evident that the B-lot of 7/8" bolts are very nearly minimum strength (102.16% of specification minimum ultimate). Results from these five tests were quite uniform so that the average critical values given here may be termed representative of each bolt in lot B. The average ultimate load was 54.3^k, and rupture occurred at 45.75^k.

Eight Z-lot bolts were tested in direct tension. The average ultimate load was 60.38^k while the average rupture load was 49^k. Rupture occurred at an elongation of approximately 0.24". Figure 11 shows three types of direct tension failures of Z-lot bolts. These types of failures may be termed typical of all 7/8" bolts tested in direct tension.

Another lot of 7/8" bolts tested in direct tension was the D-lot. These bolts were 106.7% of the specification minimum ultimate. Ultimate load was 56.7^k and the rupture load was 45.8^k. Approximate elongation of rupture was .25 inches.

Three of these lots (Q, R and S) cannot be called standard since they were made with greater than standard thread length. These lots were, however, from the same heat and were ordered especially to determine the effect of thread length on the tension-elongation characteristics. All three lots were 5 1/2" under head. Tension-elongation curves of these three lots were directly comparable and afford the opportunity to view graphically this effect of the length of thread in the grip area. (Fig. 12) At any point on this composite graph, the elongation at any load varies in some relationship to the length of thread in the grip area. Likewise, the load attained at any one elongation is related inversely to the length of thread. Then, too, the elongation at which the full threaded bolts (S-Lot) ruptured was approximately twice that of the bolt with the 2 1/4" thread length (Q-Lot). Figure 13 is a photo of one bolt from each of the lots marked Q, R and S. It is important to notice here that most of the necking occurred in the threaded portion.

Bolt lots designated T, U, V and W have similar material properties to those of the Q, R and S lots. Tests of these bolts were included in this study to serve a dual purpose:

1) As control tests for large bolted joints in which these lots of bolts were to be used as fasteners.

2) To determine the effect of grip length on the tension-elongation relationship.

These bolts ranged from 6 1/2" to 8 1/2" under head. The important point brought to light by this series of tests was that there was no apparent decrease in ultimate load carrying capacity and also no definite trend in elongations at rupture or at attainment of ultimate load (Fig. 14). At specification minimum proof load, however, the elongations are in direct relation to the grip length. The bolts of lots Q through T were approximately 102.5% of specification minimum ultimate load making them very nearly minimum strength bolts.

ASTM specifications list proof load for 1" bolts at 47.25^k while ultimate load must be at least 69.7^k. Again, two lots of bolts were tested. The first of these was the Y-lot from which five bolts were selected. The average ultimate load of these five specimens was 73.0^k while average rupture load was 62.5^k. Each bolt passed the permanent elongation at proof load check. Rupture occurred at an elongation of .38 inches.

The second lot of 1" bolts tested was designated the A-lot. It was 106.35% of specification minimum ultimate strength. Average rupture load was 63.6^k occurring at an elongation of approximately .33 inches. Figure 15 and Fig. 16 are photos of typical 1" tensile failures and Fig. 10 shows the average tension-elongation curve of the A-lot.

Results of direct tension calibration of the 1 1/8" bolts closely followed the general pattern of the 7/8" and 1" bolts. Ultimate load was 91.2^k which is 113.85% of the specification minimum ultimate. Rupture occurred at a load of 76.6^k and an elongation of .30 inches. The average tension-elongation curve for the G-lot can be seen in Fig.10.

4.3 Torqued Calibration

As was the case in the direct tension calibration tests, three sizes of bolts were tested in this phase of the program. Again, these bolts ranged from lengths of 5 1/2" to 8 1/2" under head. Only a limited number of bolts were tested to rupture for fear of causing damage to the Skidmore-Wilhelm calibrating device. Figure 17 is a tension-elongation curve of three of the lots of bolts used in the torqued calibration phase. (See Fig. 9 for tabulation of results of torqued calibration phase.)

Three bolts were selected from the B-lot to be tested by tightening the nut against the resistance of the packing washers and the Skidmore-Wilhelm. In this case the average ultimate load was 15.8% less than the direct tension ultimate (Fig. 9). Elongation at failure was 0.19 inches, also less than in the direct tension tests.

Tests of twelve Z-lot bolts revealed an average ultimate load of 55.0^k which is 8.87% less than the direct tension ultimate. Rupture load was uncertain since the tests were stopped short of failure. Judging from previous tests, however, a fair approximation of the rupture load would be 42.5^k at an elongation of .19 inches. Bolts torqued continuously to 1/2, 1 and 1 1/2 turns revealed bolt tensions and elongations similar to those of bolts which were torqued to the various turns of nut by 45 degree increments.

In tests of three D-lot bolts, an average ultimate load of 51.8^k was recorded; the reduction in strength from direct tension ultimate was approximately 8%.

As before, lots Q, R and S were tested in this phase of the program to compile further data on the effect of thread length in the grip area. Figure 18 is the resulting set of curves showing this effect. The increased thread length did increase the elongation at any given load; however, it did not tend to decrease the ultimate capacity of the bolts to any marked degree. The Q, R and S lots were respectively 94%, 88.5% and 88% of specification minimum ultimate load.

In order to study the effect of grip length on the torqued tension-elongation curve, bolts of the T, U, V and W lots were tested. As was the case in direct tension calibration, there was no apparent effect on the ultimate strength of the bolts or on the elongation characteristics beyond specification minimum proof load.

Three A-lot bolts were included in the 1" torqued calibration tests. The average ultimate load was 56.0^k while the rupture load was uncertain since none of the A-lot bolts were tested to failure.

Bolts from the Y-lot were not included in these tests.

Two G-lot bolts were tested. After the nut of the second bolt had been tightened through 1 1/4 turns the dowel pin in the Skidmore-Wilhelm calibrating device sheared allowing the piston to turn with the nut. It was decided at that point that it would be unsafe to continue testing these larger bolts in the calibrator. Prior to shearing of the dowel pin, the results of the second trial followed closely the results obtained from the first 1 1/8" bolt. Both tests followed the general trend established in the testing of 7/8" and 1" bolts by turning the nut. Ultimate load was approximately 73^k and final elongations were approximated to be about .15 inches.

4.4 Load-Unload-Reload Tests

Three 7/8" bolts from the Z-lot were chosen for these tests since the torqued calibration data for the Z-lot was most complete. Figure 19 shows a plot of tension vs. elongation for the load-unload-reload test in which load was applied and re-applied through one-half turns-of-the-nut. The ultimate strength of the bolt was not effected by the load-unload-reload procedure. Failure occurred by thread stripping after the nut had been turned through 1 7/8 turns in the sixth reloading sequence. This compares with rupture at 2 1/4 turns of the nut for a bolt which had been torqued directly to rupture in 45 degree increments of turn.

This general procedure was repeated using one full turn of the nut from the snug position rather than one-half turn. Again, ultimate capacity was not effected; however, in this case rupture occurred after only 3/8 turn in the third reloading sequence (Fig. 20). A second bolt was unloaded only once and then reloaded to failure. Rupture occurred after 1 7/8 turns of the second loading sequence. In all the torqued calibration work turns of the nut were recorded from a snugging load of 8.0^k bolt tension and not from a finger tight position as is recommended in the 1954 specification of the Research Council on Riveted and Bolted Structural Joints.

5. ANALYSIS OF RESULTS

The following discussions are based on the results of bolt calibration work done at Lehigh University.

5.1 Direct Tension vs. Torqued Calibration

Figure 21 is a typical curve comparing the load-elongation properties of direct tension and torqued calibration for one lot of bolts, the B-lot. In this, and all other lots of standard thread length bolts, the method used to induce the internal tension in the bolt had no effect on the tension-elongation relationship in the elastic range. Beyond the proportional limit, however, a difference in ultimate strength is apparent. This difference ranged from 5% to 25%, with an average decrease from direct tension ultimate of approximately 11%. It is also interesting to note the difference in total elongation which occurs when bolts are torqued to failure. The elongation at rupture for bolts of the torqued calibration tests were from 20% to 60% less than the rupture elongations recorded during direct tension calibration.

Thus the turning of the nut reduces the over-all performance of the fastener in comparison with one which is loaded in direct tension. The reduced strength in tension results from the different stress condition present when the bolt is tensioned by turning the nut and in no way indicates a deficiency on the part of the bolt. Frictional resistance between the nut and bolt threads transforms some of the applied energy into torsional shear stress thus changing the tension-elongation relationship. Evidently, this frictional resistance between the bolt and nut threads becomes critical when the material of the threaded portion of the bolt is stressed beyond the proportional limit and takes on plastic deformations which cause thread binding. Below the proportional limit thread deformations are small and the tension elongation relationships are the same for the two method of calibration.

5.2 Effect of Grip

Test results from thirty 7/8" bolts having grip lengths of from 4 inches to 6 3/4 inches (lots Q, T, U, V, W), indicate that the grip length has no appreciable effect on the tension-elongation characteristics of the bolts. These bolts had 1/2 to 3/4 inches of thread in the grip. A close examination of Fig. 14 at the elastic proof load reveals that, while the bolt is still elastic the amount of elongation is directly related to the length of grip. (The exact figures are tabulated in Fig. 9). This is true for both direct tension and torqued calibration. As the tension is increased beyond proof load, the threaded portion behaves plastically while the shank remains elastic; therefore, most of the additional elongation takes place in the threads. This plastic deformation of the threaded portion beyond proof load overshadows the relatively small elastic elongations which occur in the bolt shank. For this reason the relationship between grip length and elongation no longer holds true with loads greater than proof load.

5.3 Effect of Thread Length

From the previous discussion, it would seem logical to assume that since most of the elongation occurs in the threads, the length of thread in the grip area will have a marked effect on the tension-elongation relationship. This is the case (Fig. 12 and 18). Notice in the photo (Fig. 13) that in the case of the full-threaded bolt, necking is apparent through out the entire grip length; in the R-lot, which was threaded through approximately half of the four-inch grip, one can see distinctly that all appreciable necking has taken place in the threaded portion only. Therefore, most of the elongation which occurs as the bolt is stretched beyond proof load takes place in the threads within the grip. Further, a close examination of the 1954 specification recommendation for choosing bolt length reveals that this length of thread in the grip area will not vary more than approximately 1/4". From this fact it is evident that if bolt lengths are chosen in the proper way, the length of thread in the grip area will be relatively constant; therefore, the elongations which occur in any given grip will also be approximately the same.

5.4 Evaluation of Turn-of-Nut Procedure

In standard erection precedures the bolt tension can be most economically induced by the turn-of-nut method. The torqued calibration relationship, then, best simulates the actual condition of bolts installed in the field. Figure 22 is a curve constructed from data obtained by torquing several Z-lot bolts continuously to 1/2 turn, 1 turn, and 1 1/2 turns respectively from the "snug" postion. These points were plotted on the average torque calibration curve of the Z-lot, obtained by 45 degree increments of turn, and the scatter of these points was then represented by cross-hatched zones in order to present a better idea of the area of the curve involved. Notice that the turn-of-nut precedure of first drawing the plies into contact with the impact wrench and then turning the nut one-half turn induces a tension in the bolt greater than the specified minimum tension of 0.9 E.P L. In fact, the tension induced by this method is approximately 30% greater than the minimum.

The one turn-of-nut zone falls at the ultimate strength of the bolt. This zone is somewhat higher than would be a zone for one turn-of-nut from a finger tight position, the tightening procedure used by some erectors.

Figure 23 is a bolt tension distribution chart plotted for six bolted butt joints tested at Lehigh University.(13) Information gathered in this calibration study was used to plot the average tension-elongation curves. The bolt elongation histograms below were plotted to the same abscissa as the load elongation curves to show bolt tension distribution throughout joints assembled using the 1/2 turn-of-nut method. It is important to notice here that despite the apparent scatter in elongations, little difference in bolt tension is found when the elongations are projected up to the calibration curve. This is due to the fact that the turn-of-nut method causes the bolt to deform beyond the elastic range into the relatively flat elastic-plastic range. Therefore, a considerable variation in elongations results in relatively small variations in induced tension or clamping force. Similar distribution charts plotted for other large joints in the Lehigh project reinforce these findings and attest to the reliability of the turn-of-nut method.

According to a suggested procedure for the turn-of-nut method(10) 3/4 and 7/8 bolts used with grip lengths of between five and ten inches and 1'; 1 1/8' and 1 1/4' bolts with eight to twelve inch grips should receive 3/4 turns from the snug position rather than the customary 1/2 turn. This requirement is intended to insure, beyond a doubt, that an adequate margin of safety against insufficient internal tension is achieved. Figure 24 is a plot of per cent of minimum allowable internal tension vs. grip length in inches for a 7/8" bolt. Notice that a grip of as large as 6 3/4" (the largest included in this study) the internal tension at one-half turn of the nut is still 125% of specification minimum. Moreover, it was found that the average percentage of specification minimum bolt tension for all grips tested was 128%. For general interest the same comparison was made at 3/4 turns-of-nut. In this case the average internal tension for all grips was 143% of specification minimum tension. Ultimate load, according to a similar comparison occurs at approximately 157% of minimum tension. These figures indicate that the portion of the turn-of-nut method controlling the increased amount of rotation for grip greater than 5" is quite conservative. All bolts used in these comparisons were from the same heat and exhibited similar material properties. By the same token, they were minimum strength bolts (102.5% of specification minimum ultimate). Then, too, the 1/2 turns were recorded from a snugging tension of 8.0^k. Actual measurements of bolts in a structural joint after snugging have exhibited internal tensions in the neighborhood of 15.0^k. These facts illustrate the using 3/4 turn of the nut for 7/8" bolts with grips greater than 5" may be a practice which is unnecessary. However tests of large joints have shown no detrimental behavior due to this degree of tightening.

5.5 Slip Coefficient

The slip coefficient of a single lap joint has been defined as:

$$K_{slip} = \frac{P_s}{n \times T_i(\text{avg.})}$$

In section 1.1 it was stated that reported values of "coefficient of friction" vary depending upon when the internal tension measurements were taken and also on the procedures used for establishing the calibration relationships. Therefore, if one uses slip coefficient rather than coefficient of friction, the only further qualification necessary would be to state whether a direct tension or torqued calibration curve had been used to determine $T_{i(avg.)}$.

5.6 Clamping Force

It has been pointed out previously that the torqued calibration procedure simulates actual field conditions more closely than the direct tension procedure. Figure 25 is a non-dimensional plot of induced tension at any particular turn-of-nut (T_a) divided by ultimate tension (T_u) vs. elongation at any particular turn-of-nut (e_a) divided by elongation at failure (e_f). Values of ultimate tension and elongation at rupture were taken from average torqued calibration curves for bolts of the same lot. Data used to plot this curve was compiled from torqued calibration tests of four different lots of bolts including 7/8", 1" and 1 1/8" diameters. In the shaded portion of the curve corresponding to one-half turn-of-nut, although the tension in the bolt is 90% of ultimate, less than 1/5 of the total elongation has been utilized in attaining this 90% of available clamping force. By a similar comparison, one full turn of nut would induce maximum tension in a bolt while using approximately half the total available elongation. Thus in order to achieve a 10% increase in clamping force the factor of safety against rupturing the bolt during tightening is reduced from 5 to 2.

The clamping force at one-half turn-of-nut from the snug position may be approximated in the following way. The average "reduction in strength" due to torqued calibration (Fig. 20) is 10.7%. In addition, the tension in a bolt at one-half turn-of-nut is approximately 90% of the torqued ultimate which corresponds to a further decrease in direct tension ultimate of 8.23%. Therefore, the clamping force in a bolt which is torqued one-half turn after snugging can be approximated as 80% of the direct tension ultimate load.

5.7 Re-use of High Strength Bolts

Figure 19 shows the complete test history of a 7/8" A 325 bolt which was tested according to the load-unload-reload procedure described in Section 4.4. Load was applied a total of seven times without bolt failure although each subsequent loading tended to decrease the factor of safety against failure. In Figure 20 the same test procedure was used except that load increments were established by full turns of the nut rather than the specified one-half turn. In this case, the factor of safety against failure was greatly reduced since the bolt failed after 3/8 turn-of-nut in the fourth loading sequence. In view of these few limited tests, it seems entirely safe to re-use high strength bolts provided the stress history of the bolt is known and the installation well controlled by field inspection. The number of times a bolt could be re-used would then depend on the factor of safety required for the case in question.

6. CONCLUSIONS

The following conclusions are based on observations made from test results of 110 high strength bolts having 7/8", 1" and 1 1/8" diameters and varying from 5 1/2 to 8 1/2 inches under head.

1. When internal tensions are induced in a bolt by turning the nut against the resistance of the gripped material, both ultimate strength and potential elongation are less than would be obtained if the internal tension were induced by pulling the bolt in direct tension. Ultimate strengths are approximately 11% less than direct tension ultimate strengths, and the elongations at rupture are 20% to 60% less than the elongations at rupture in direct tension calibration.

2. Grip length has no appreciable effect on the tension-elongation characteristics of high strength bolts (Figs. 13, 23).

3. Most of the elongation which occurs as bolts are tensioned takes place in the threaded portion within the grip. Therefore, thread length in the grip area, and not grip length, is chiefly responsible for increased elongations. (Figs. 11, 17)

4. The turn-of-nut method for installing high strength bolts produces adequate and consistent bolt tensions. The three-quarter turn stipulation of the turn-of-nut method for 7/8" bolts with grips greater than 5 inches is conservative; it is not, however, detrimental to the performance of bolts installed according to this recommendation. (Figs 21, 22, 23 and 24)

5. The clamping force in a bolt which has been properly installed according to the turn-of-nut method can be approximated as 80% of the direct tension ultimate load. (Section 5.6)

6. It appears safe to re-use high strength bolts which had previously been properly installed according to the turn-of-nut procedure as long as proper control is exercised during the second installation. For erection purposes bolts can be re-used as often as five times without reaching ultimate and still have a factor of safety against rupture of approximately 2. (Figs. 19, 20)

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7. APPENDIX

7.1 Definition of Terms

1. Bolt Calibration- the relating of internal bolt tension to some other readily observed quantity.

2. Direct Tension Calibration- the establishing of a tension-elongation relationship determined by pulling a single bolt in direct tension at a precise grip.

3. Torqued Calibration- the establishing of a tension-elongation relationship determined by elongating a single bolt by turning the nut against the resistance of the gripped material.

4. Initial Tension (T_i)- the tension or clamping force in a bolt after a joint is completely bolted but under no external load.

5. Tension at Slip (T_s)- The tension or clamping force in a bolt when the joint is subjected to an external load equal to the slip load (P_s).

6. Snug- the expression used to describe the tightness of a bolt before beginning the turn-of-nut. Snug is indicated by the impact wrench when impacting begins.

7. Snugging Tension- the tensile load induced in a bolt to simulate the snug position.

8. Slip Coefficient (K_s)- $\frac{P_s}{n \times T_{i(avg)}}$ where P_s is the load at first major slip; $T_{i(avg)}$ is the average bolt tension; n is the number of bolts in the pattern.

9. Zero Length- the length of the center drilled bolt before any internal tension is present.

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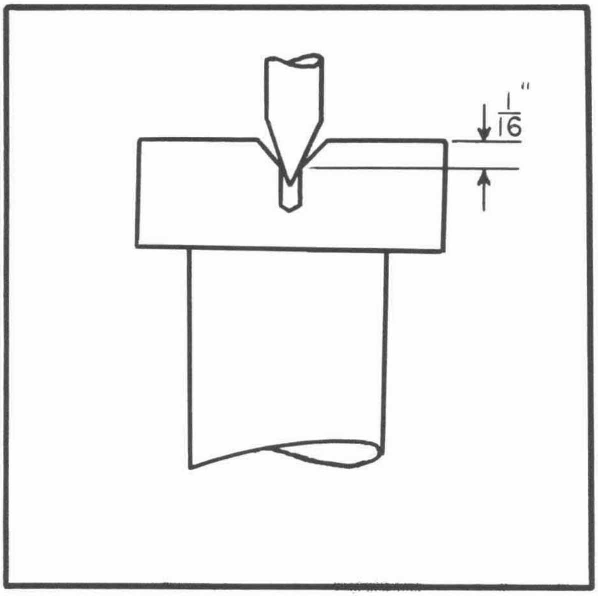

Fig. 1 Sketch of Properly Centerdrilled Bolt

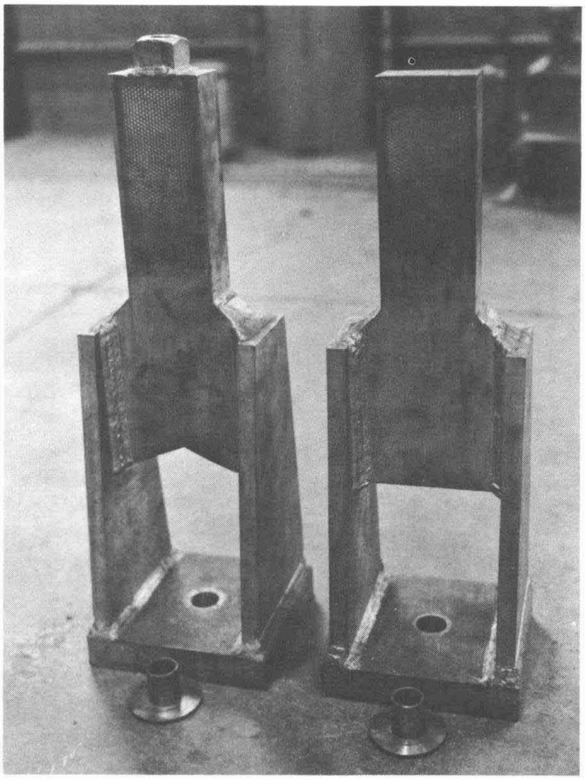

Fig. 2 Tension Grips and Inserts

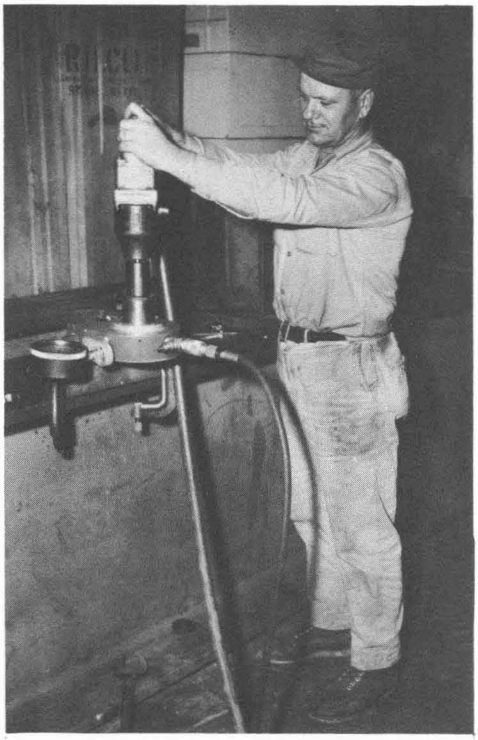

Fig. 3 Torqued Calibration of a Bolt in the Skidmore-Wilhelm Device

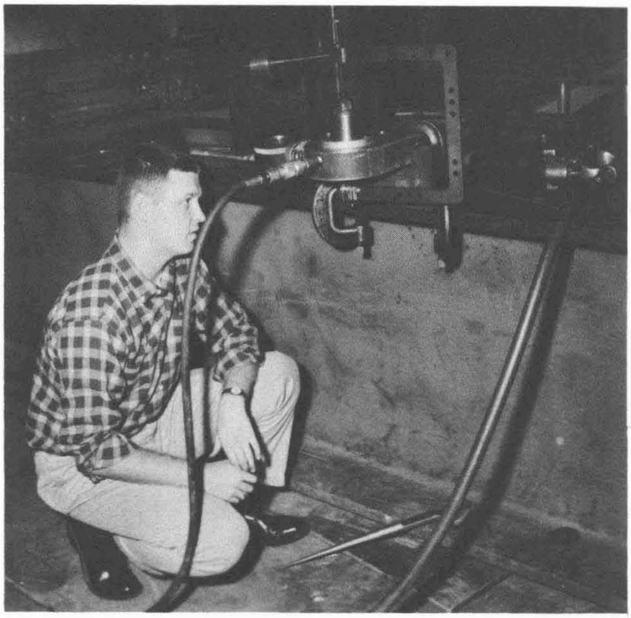

Fig. 4 C-Frame Extensometer in Place, Torqued Calibration

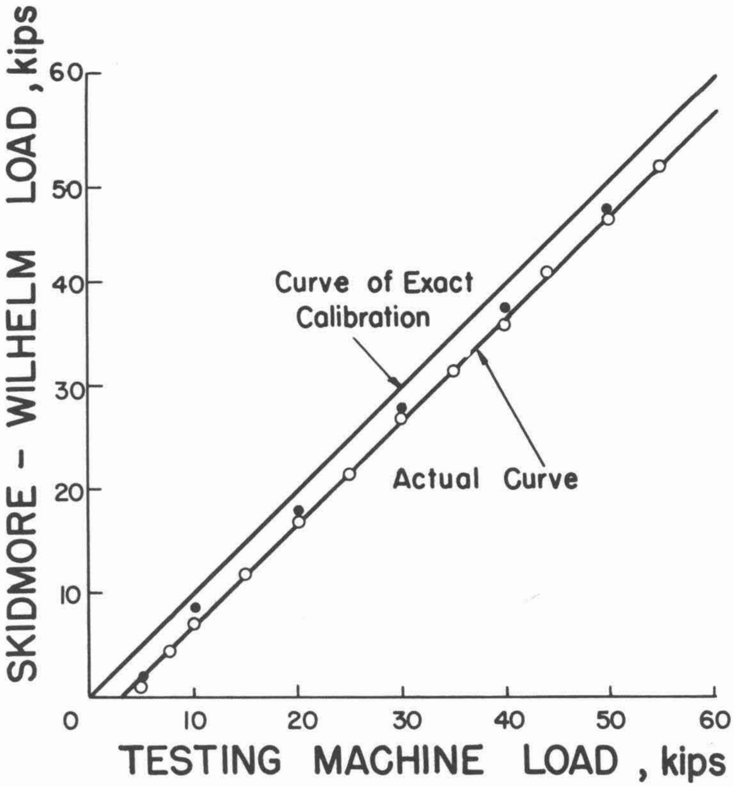

Fig. 5 Skidmore-Wilhelm Calibration Curve

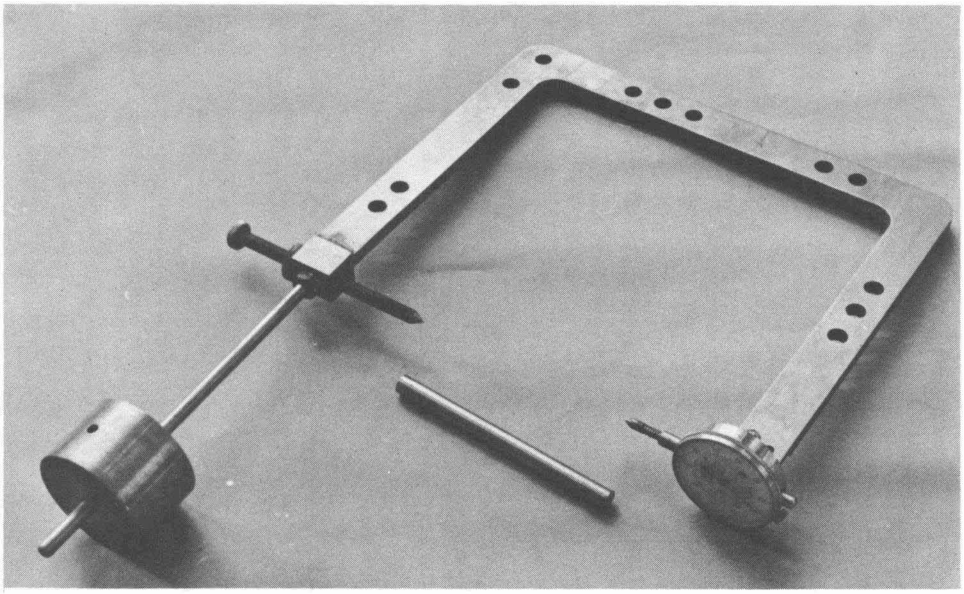

Fig. 6 C-Frame Extensometer and Zero Bar

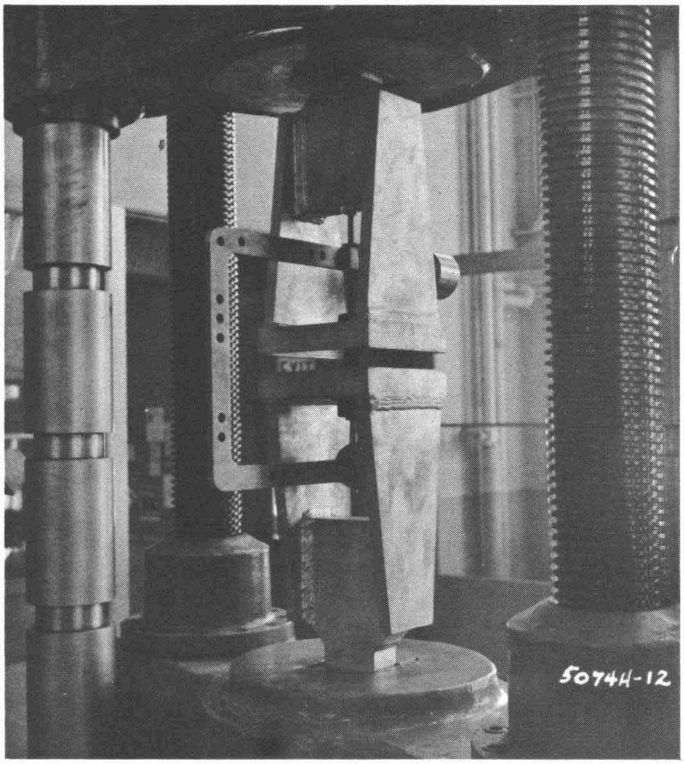

Fig. 7 Direct Tension Calibration

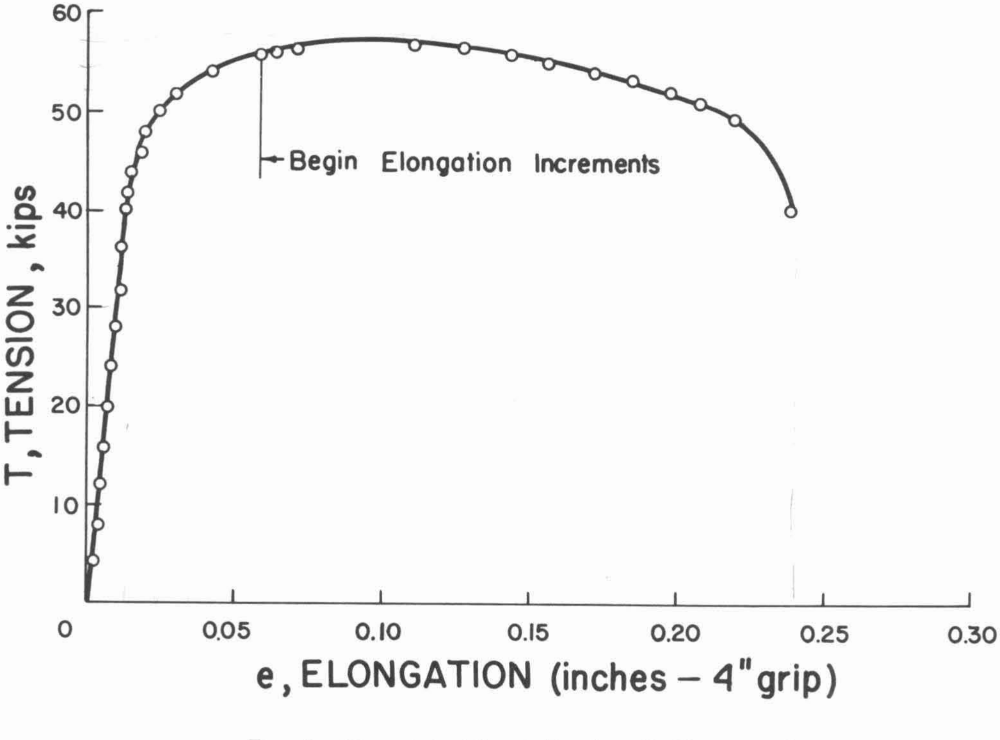

Fig. 8 Complete Direct Tension Calibration Curve

RESULTS OF BOLT CALIBRATION

	Units	B-Lot	D	Z	Q	R	S	T	U	V	W	A	Y	G
Size (nominal diameter)	in.	7/8	7/8	7/8	7/8	7/8	7/8	7/8	7/8	7/8	7/8	1	1	1 1/8
Grip Length	in.	4	4	4	4	4	4	4.75	5.25	6	6.75	4	4	4
Thread Length	in.	2	2	2	2	3.25	5.50	2.25	2.25	2.25	2.25	2.25	2.25	2.50
Length Under Head	in.	5.50	5.50	5.50	5.50	5.50	5.50	6.50	7	7.50	8.50	5.50	5.50	6
Stress Area	sq. in.	.462	.462	.462	.462	.462	.462	.462	.462	.462	.462	.606	.606	.763
Spec. Min. Proof Load	kips	36.1	36.1	36.1	36.1	36.1	36.1	36.1	36.1	36.1	36.1	47.3	47.3	56.5
Spec. Min. Ult. Load	kips	53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2	53.2	69.7	69.7	80.1
Mill Report Ult. Load	kips	54.2	54.1	59.5	55.9	55.9	55.9	56.1	56.1	56.1	56.1	73.5	74.2	90.0
DIRECT TENSION CALIBRATION														
Number Tested		5	5	8	3	3	3	3	3	3	3	5	5	5
Ultimate Load	kips	54.3	56.7	60.4	54.0	52.2	53.8	54.8	55.2	53.6	55.1	74.1	73.0	91.2
% of Spec. Min. Ult. Load	%	102.2	106.7	113.6	101.5	98.2	101.2	102.8	103.8	100.8	103.6	106.4	104.7	113.9
Rupture Load	kips	45.8	45.8	49.0	42.5	35.0	43.3	45.3	46.7	45.9	46.3	63.6	62.5	76.6
Elong. at EPL	in.	.011	.009	.009	.011	.016	.020	.013	.014	.016	.018	.011	.011	.011
Elong. at Ult. Load	in.	.015	.128	.135	.16	.25	.38	.14	.17	.17	.163	.18	.22	.20
Elong. at Rupture Load	in.	.31	.25	.242	.36	.44	.60	.35	.307	.333	.34	.33	.38	.30
TORQUED CALIBRATION														
Number Tested		3	6	20	4	3	3	3	3	3	3	3		2
Ultimate Load	kips	45.2	51.8	55.0	50.0	47.0	46.2	52.0	51.5	50.0	51.5	56.0		73.0
% of Spec. Min. Ult. Load	%	85.0	97.5	103.4	94.0	88.5	88.0	97.8	96.8	94.0	96.8	80.3		91.1
Rupture Load	kips	40.0	42.0	43.5	44.0	42.0	43.8	44.0	44.5	43.5	44.0	47.0		66.0
Elong. at EPL	in.	.011	.010	.010	.115	.027	.032	.015	.015	.017	.019	.016		.012
Elong. at Ult. Load	in.	.015	.057	.069	.12	.19	.025	.110	.15	.13	.14	.053		.080
Elong. at Rupture Load	in.	.16	.174	.19	.228	.325	.39	.206	.24	.258	.235	.120		.150
% Reduction in Strength from Direct Tension Ultimate	%	16.7	8.6	8.9	7.4	9.9	14.1	5.1	6.7	6.7	6.6	24.4		20.0

Fig. 9 Table of Test Results

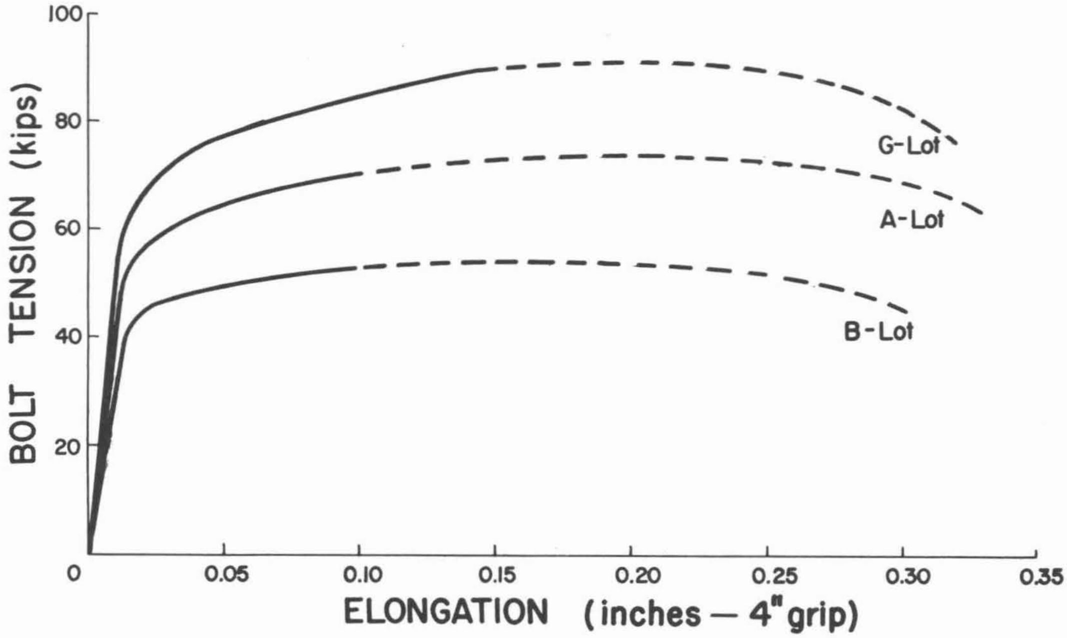

Fig. 10 Direct Tension Calibration, 7/8", 1" and 1 1/8" Bolts

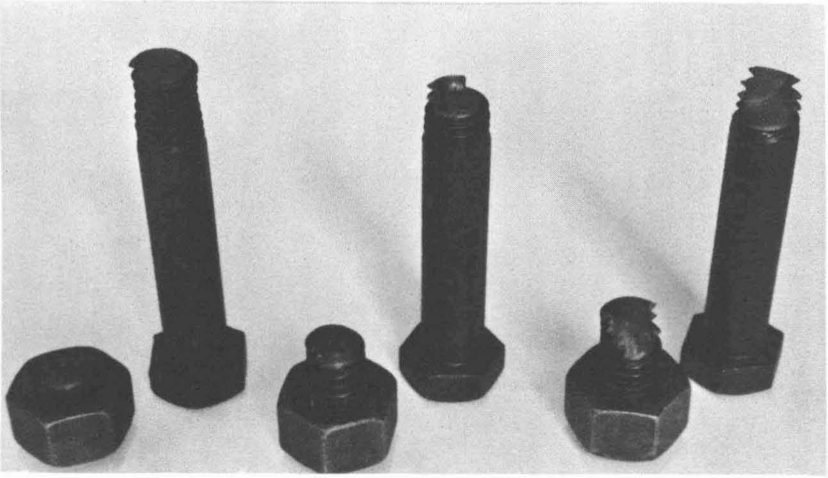

Fig. 11 Typical Z-Lot Failures, Direct Tension

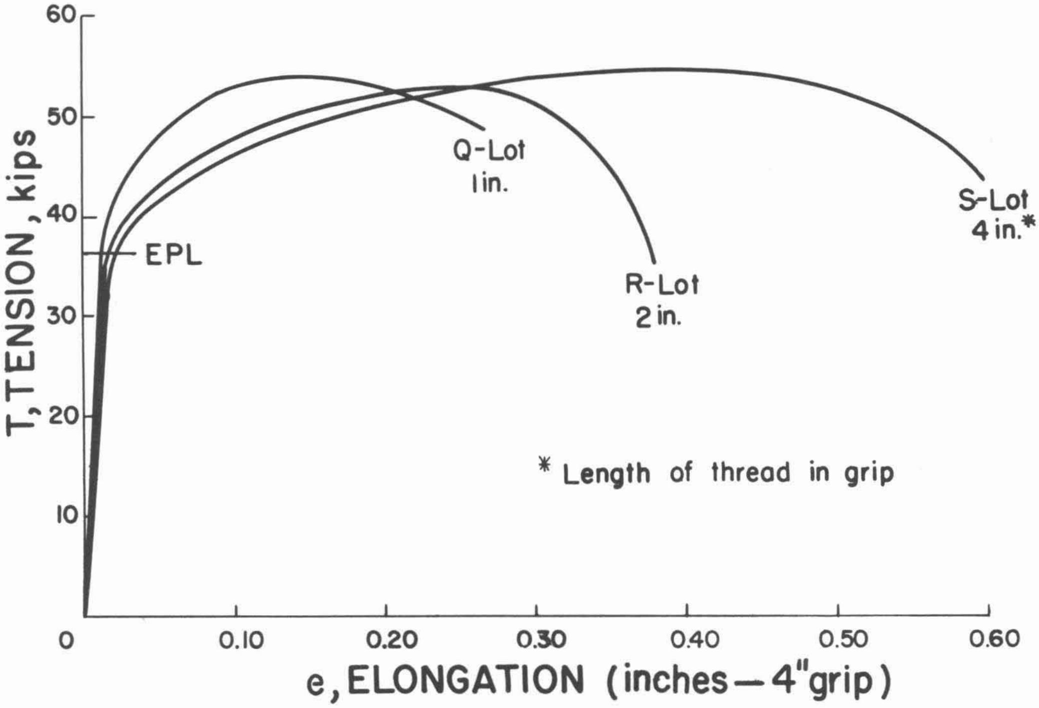

Fig. 12 Effect of Thread Length on the Tension-Elongation Relationship
Direct Tension Calibration

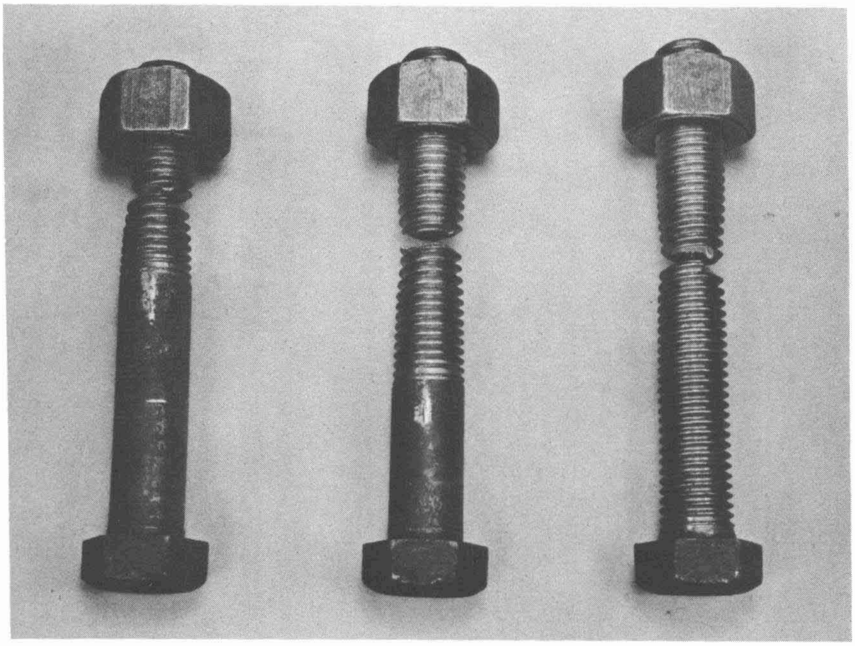

Fig. 13 Direct Tension Failures of Q, R, and S Bolts

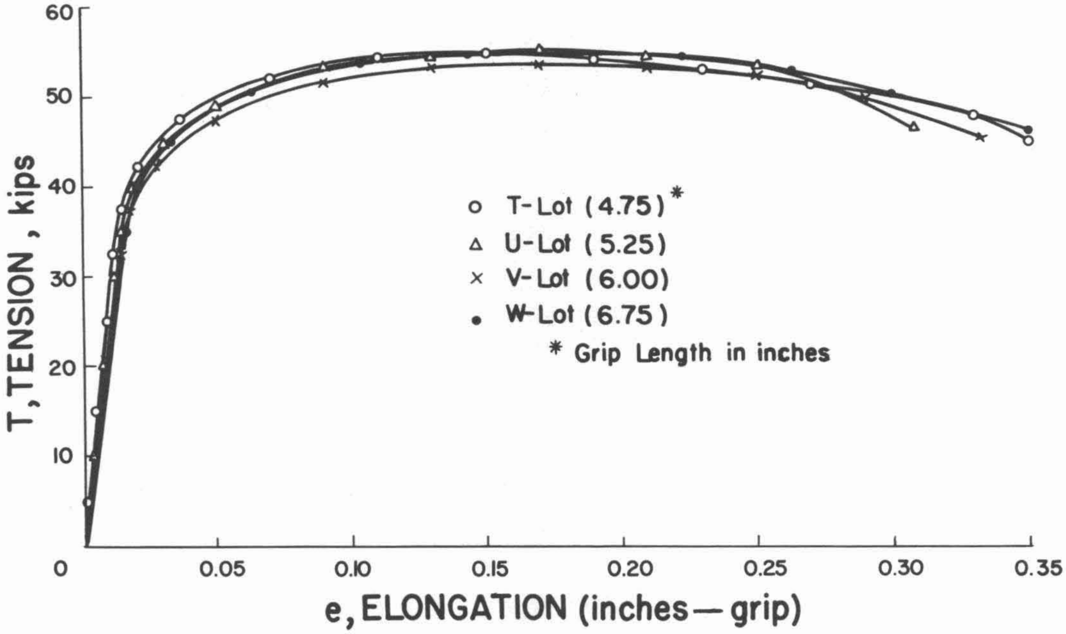

Fig. 14 Effect of Grip Length on the Direct Tension-Elongation Relationship

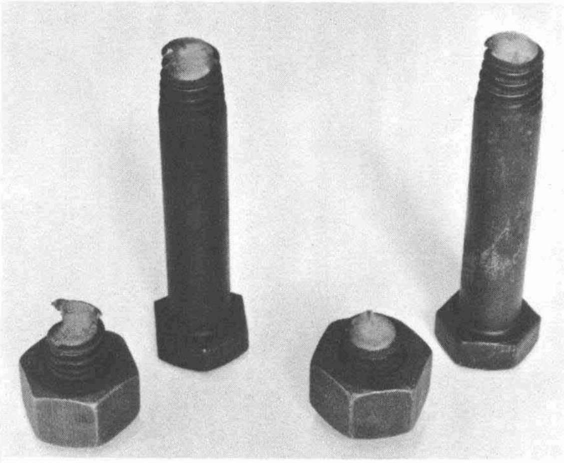

Fig. 15 1" Tensile Failures

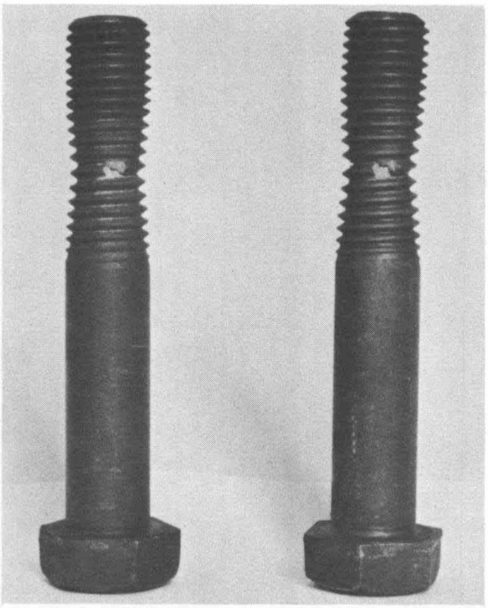

Fig. 16 1" Tensile Failures

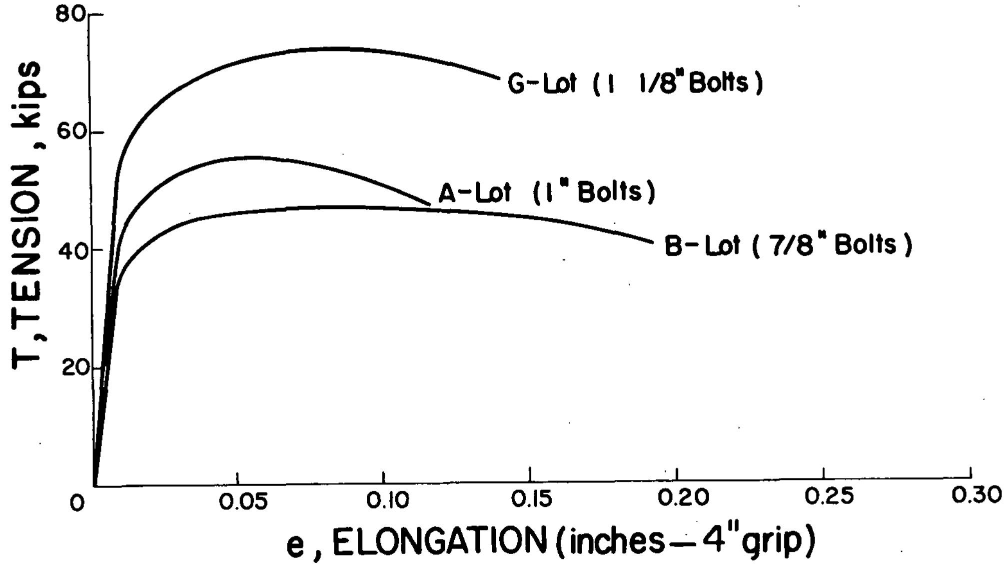

Fig. 17 Tension-Elongation Relationships, Torgued Calibration

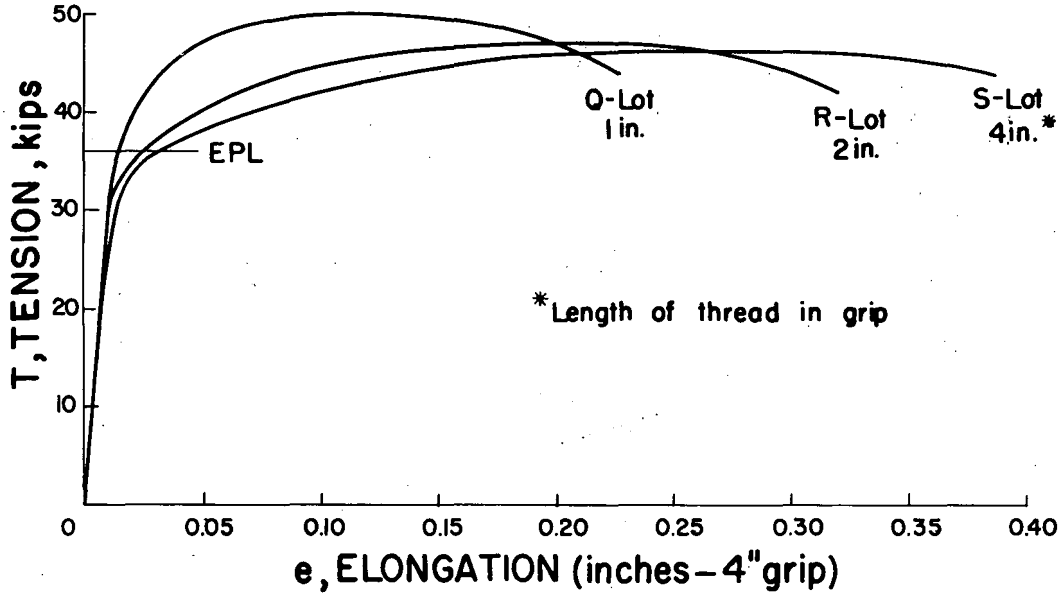

Fig. 18 Effect of Thread Length in Grip-Area, Torqued Calibration

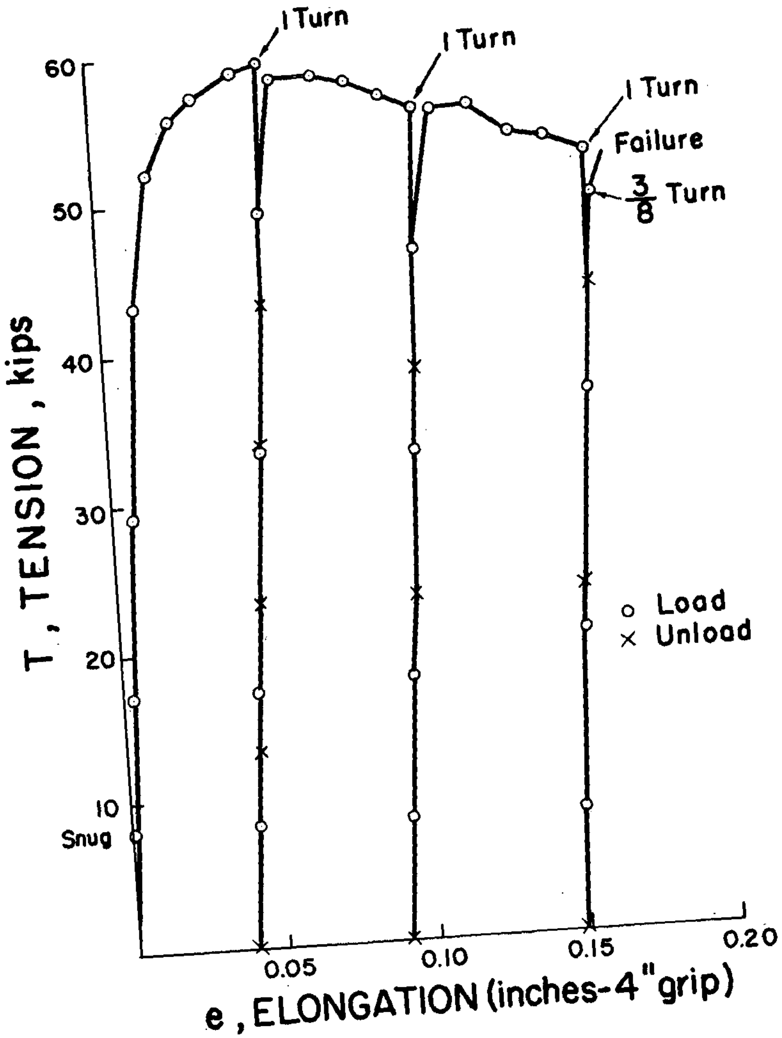

Fig. 19 Load-Unload-Reload Test Using 1/2 Turn-of-Nut

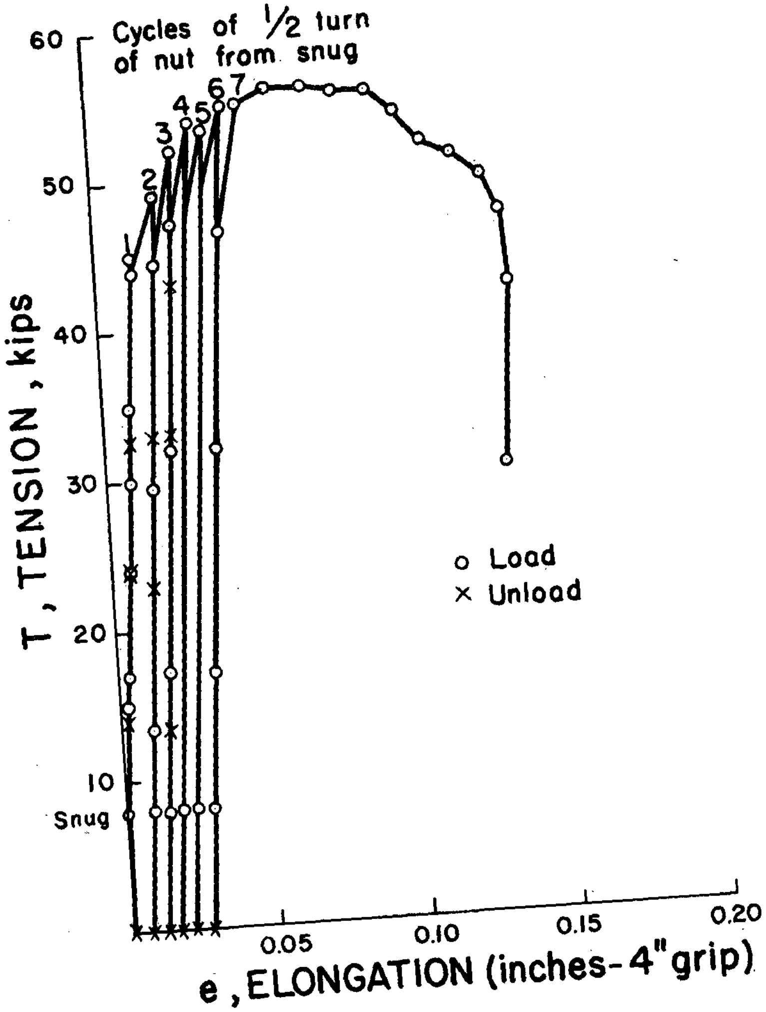

Fig. 20 Load-Unload-Reload Test Using 1 Turn-of-Nut

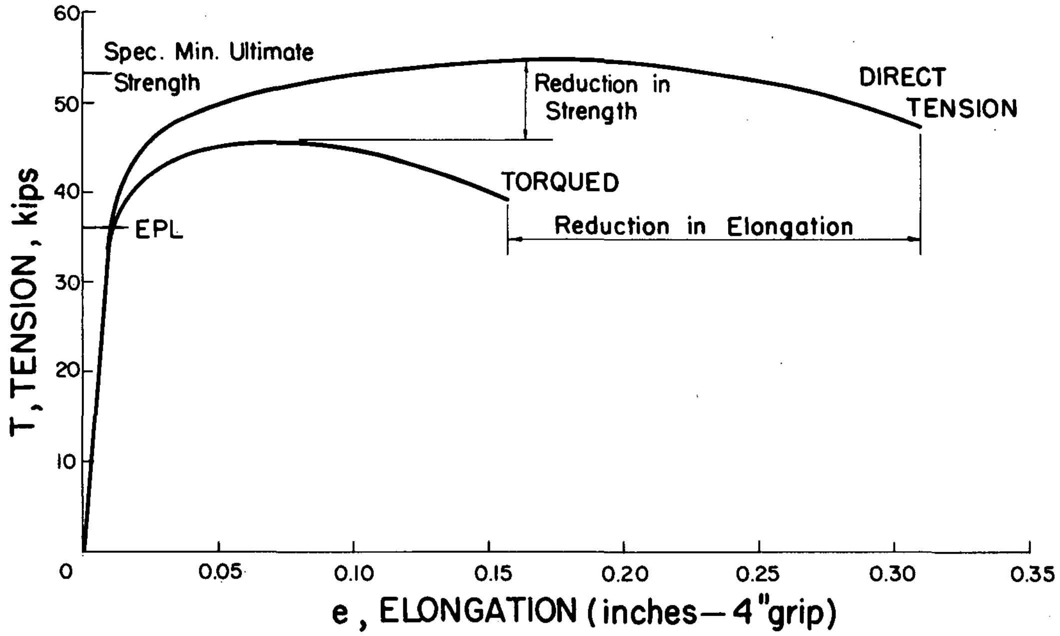

Fig. 21 Effect of Calibration Procedure on the Tension-Elongation Relationship

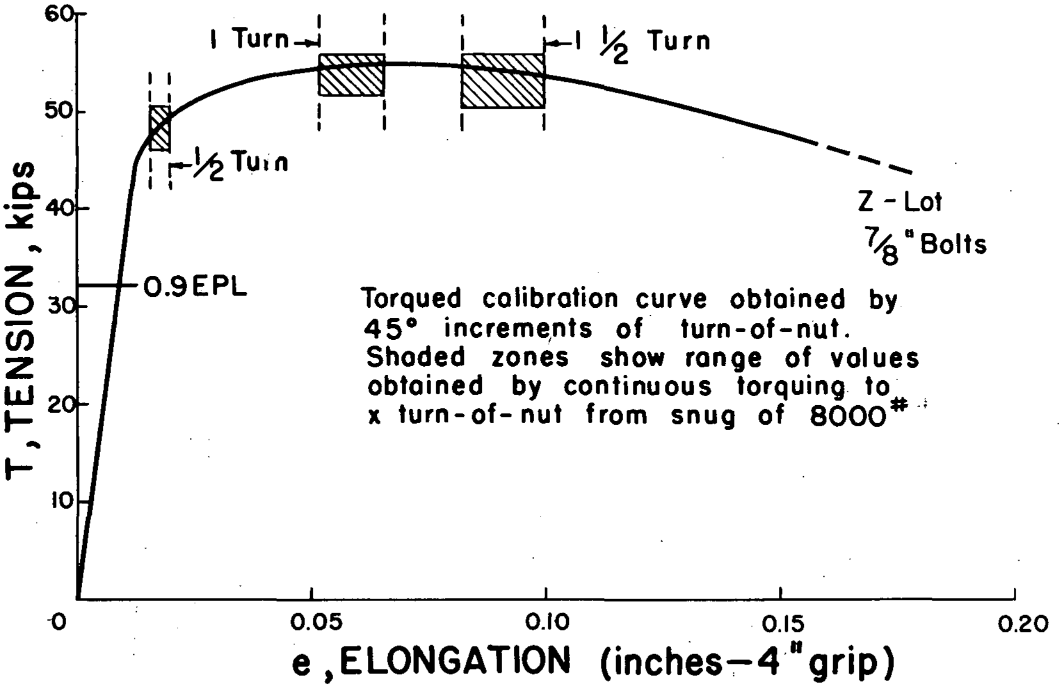

Fig. 22 Tension-Elongation Zones Produced by Various Turns-of-Nut

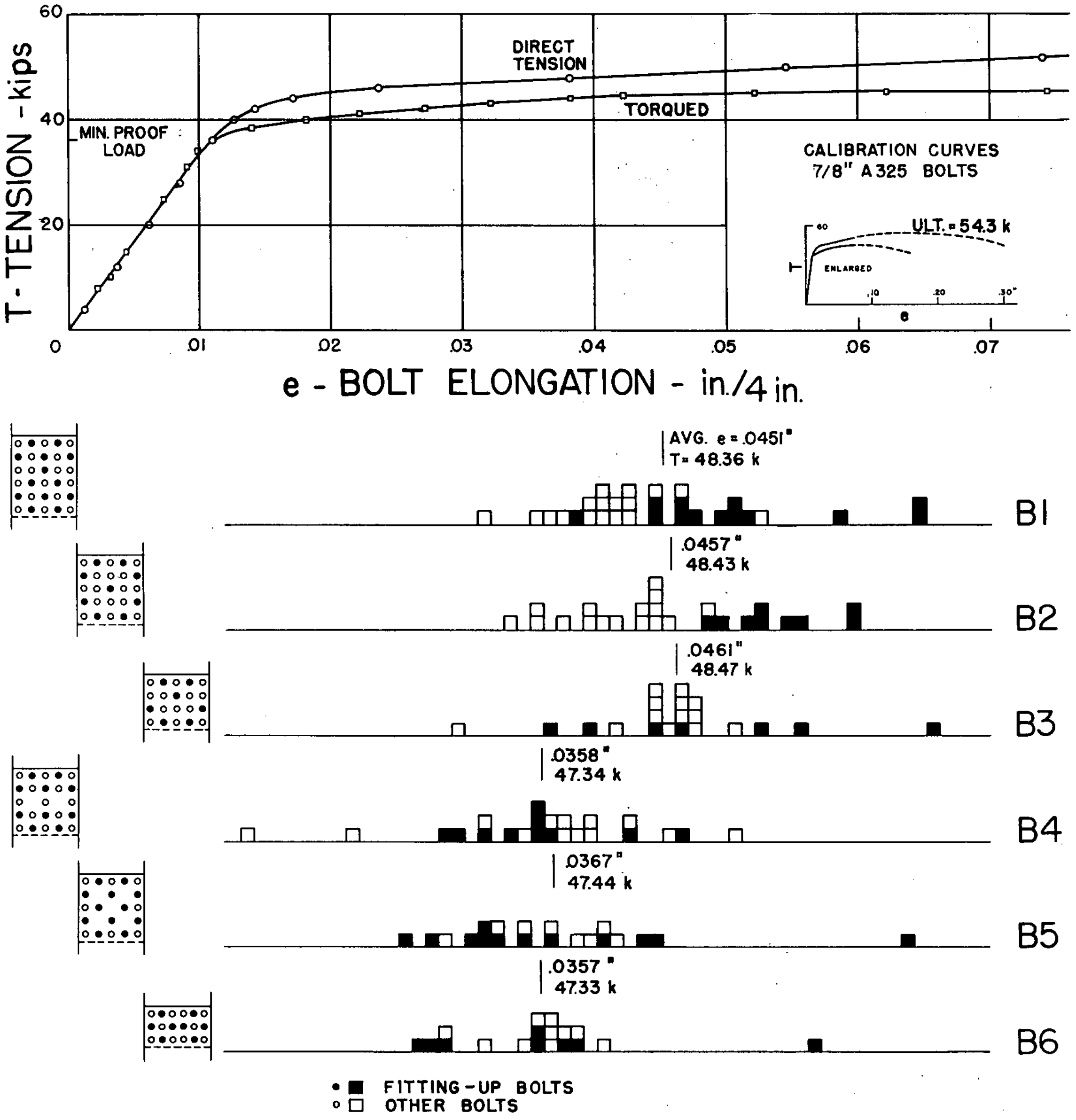

Fig. 23 Bolt Tension Distribution

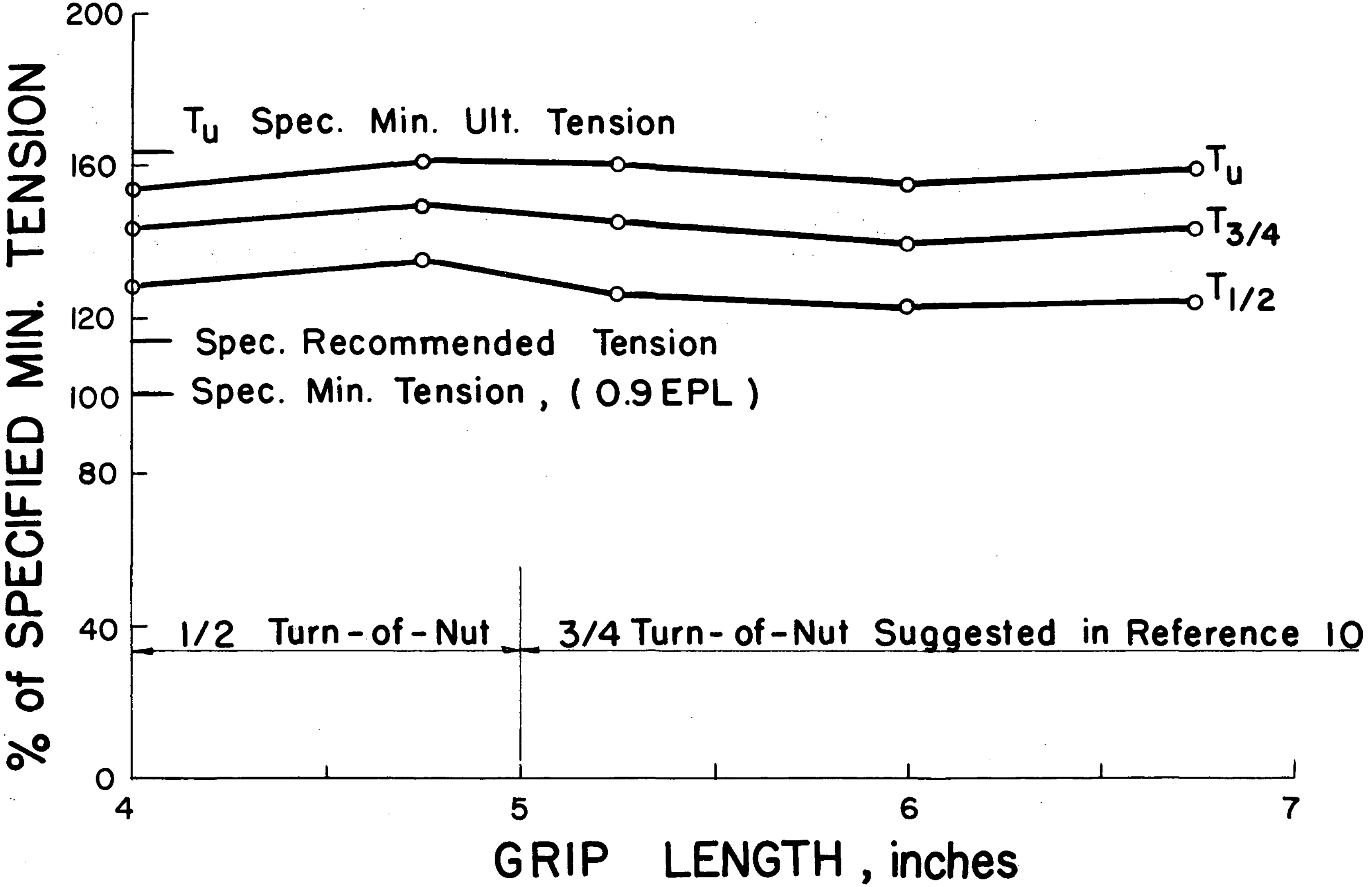

Fig. 24 Effect of Grip Length on Bolt Tension for 7/8" Bolts

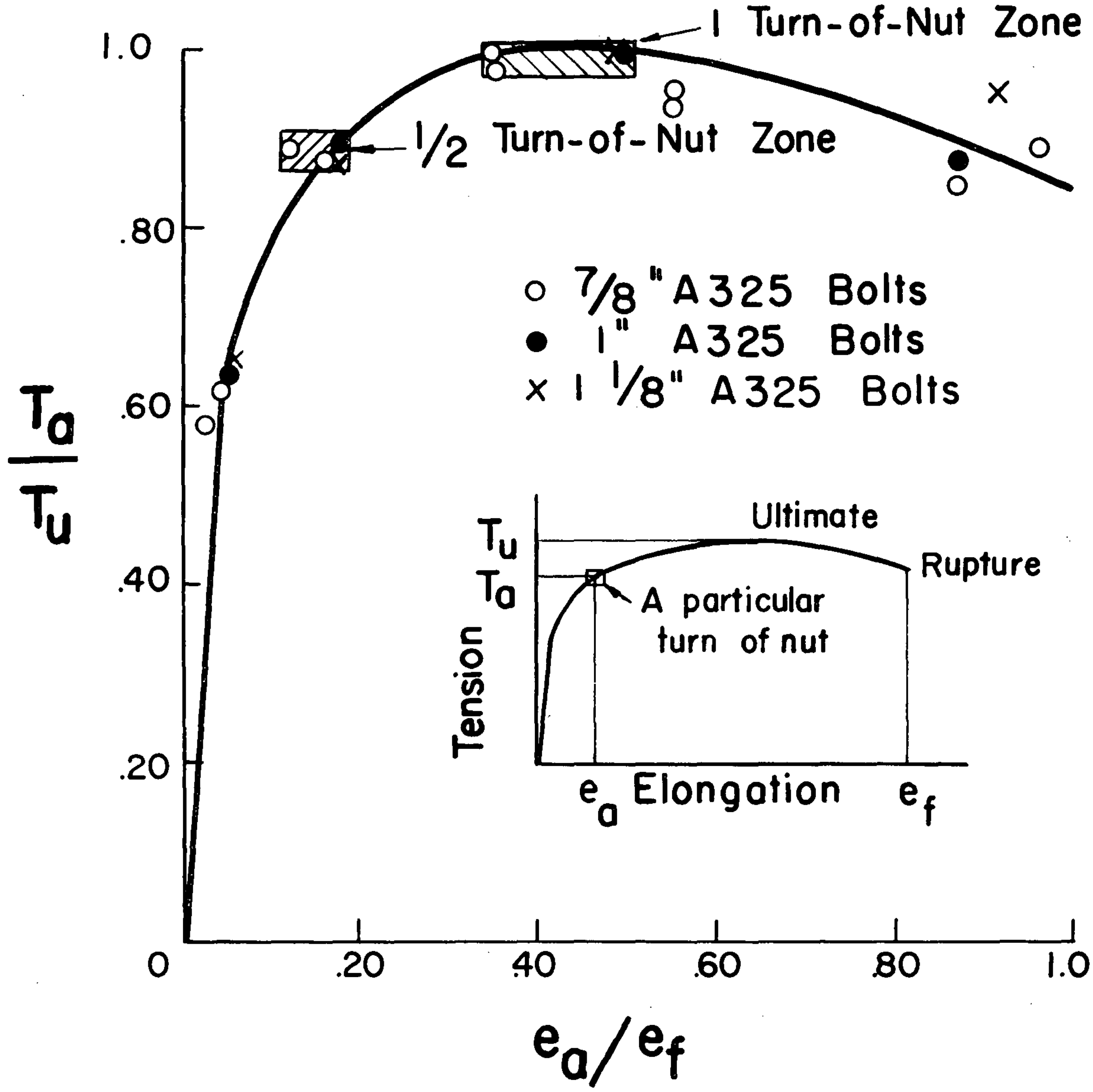

Fig. 25 Efficiency of Turn-of-Nut Method