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CALIBRATION AND INSTALLATION OF HIGH STRENGTH BOLTS

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SYNOPSIS

For the purpose of this report bolt calibration has been defined as the relating of internal bolt tension to some other readily observed quantity; e.g., bolt used in these investigations were ASTM A-325. This report is intended to review the need for bolt calibration and available procedures, to discuss the procedure used at Lehigh, and to present information on the turn-or-nut method for installing high strength bolts.

1. 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

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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 changes in the grip length as the gripped material deforms under load. Thus, if one wished 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.

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

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

If bolts are tightened into the elastic-plastic range where 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 the average bolt elongation (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 divising 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 ficticious 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 dixmissed 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

e) Internal Tension vs. Turn of Nut

Each method presents its own advantages and disadvantages.

Tension vs. Torque

Turning a nut against the resistance of gripped material induces an internal tension in a bolt. Turning of the nut requires application of a torque because of thread friction and friction on the bearing surface of the nut. It is possible to relate the induced tension and the applied torque as measured by a torque wrench and a number of investigators have done so for the high strength structural bolt(1,2,3). Because this relation depends so much on the condition of the surface of the threads, nuts, and washers it is subject to a wide variation. Nevertheless, the 1954 specification of the Research Council on Riveted and Bolted Structural Joints(4) listed a table of equivalent torques as a guide to proper bolt tensions.

Experience in the field use of bolts has confirmed the erratic nature of the torque-tension relation. As a result the 1960 specification of the Research Council(5) now requires that the impact wrenches relying on torque control "...shall be calibrated by tightening, in a device capable of indicating actual bolt tension, not less than three typical bolts from the lot to be installed". When bolts from different lots are to be tightened the wrench must be recalibrated.

Despite the shortcomings of this type of control the inspector must resort to it for want of a better method. The 1960 specification(5) requires that the inspectors' manual torque wrench be calibrated in a fashion similar to above.

Tension vs. Elongation

A tension-elongation relationship has been used by many laboratory investigators. The method consists of stretching the bolt by some controlled load and measuring the resulting change in length with an extensometer. If the bolt is to be tightened in the elastic range only, each bolt may be calibrated individually before installation in the connection(6). If bolts are to be tightened into the plastic range it is necessary to develop a tension-elongation curve for typical bolts of the lot and to assume that bolts installed in the connection follow the same curve(7).

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 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 strain gages on the unthreaded shank of the bolt(2,8,9). This method probably is restricted to laboratory use, for when used in connections, it requires the use of oversize holes to provide clearance for the gages and the bolt heads must have small holes drilled in them to accommodate the lead wires. If the shank is stressed into the plastic range the SR-4 gage loses its effectiveness.

Tension vs. Load Cell Output

The load cell is a cylindrical piece of steel through which the bolt is inserted. Dimensions of the cylinder are chosen so that the cell remains elastic under all conditions of bolt tension. SR-4 gages are mounted on the outside of the load cell rather than on the bolt shank.

The load cell has proven useful in studies of bolt relaxation over a period of time(10). When used to control tensions in bolted connections it has the disadvantage of reqiring a bolt longer, by the length of the cell, than normally used for a given grip. Thus, it is strictly a laboratory device.

Tension vs. Turn-Of-Nut

As a nut is tightened against the resistance of the gripped material the bolt length within the grip is forced to elongate. Theoretically, if the threads are rigid, one complete turn of the nut will cause the bolt to elongate one pitch. Actually this is not quite true because of thread deformations that occur. It is possible to determine experimentally the relationship between the amount of rotation of the nut and the elongation of the bolt or, the tension in the bolt.

The first turn-of-nut method developed for the structural application of high strength bolts(11) advocated one full turn from finger tight. A subsequent version of this turn-of-nut idea(12) uses a one-half turn-of-nut from a "snug" position.

Controlling tension by the turn-of-nut is essentially a strain control and the effectiveness of the method depends primarily on three factors:

(1) The consistency of the starting point

(2) The accuracy to which rotation increments are measured

(3) The amount of tension desired

If the first two of these contributing factors are carefully controlled, desired tensions can be obtained with accuracy in both the elastic and plastic regions of a bolt's stress life. However, when one accepts the idea that high bolt tensions--into the plastic region-- are desired and are not detrimental to the performance of the bolts under load, the real merit of the method appears. In this region the load elongation curve is relatively flat and variations in elongation resulting from lack of control of items (1) and (2) result in small tension variations. It is for this reason that the turn-of-nut method is a good field procedure for controlling bolt tension.

The number of bolts to be calibrated was quite large in view of the over-all plans of the project at Lehigh 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 would dependably produce similar results over a period of years.

After studying and considering each method of bolt calibration it was decided to install bolts by the turn-of-nut method and to check the tensions by calibration curves established by the tension-elongation procedure. Since the turn-of-nut procedure(12) was used in bolting the joints, continuous readings of tension during tightening 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

To induce an internal tension in a bolt, it is necessary to stretch the bolt in some way. This can be accomploshed 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 bolts are usually tightened with a pneumatic impact wrench. It has been reported that tensions induced by this method are ultimately lower than tensions induced by a direct axial pull on the bolt. H.O. Hill(13) 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 A325 bolts stipulates that direct tension type of test. In summary, then, while torqued calibration best simulates actual field conditions which would be encountered in bolts installed in the field, the direct tension method is best suited for laboratory and control testing. Both procedures have been investigated in the tests conducted at Lehigh.

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 tested included 7/8", 1", 1 1/8" diameters ranging 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". Thread lengths were determined according to the recommendations of the 1954 specification; 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 combination drill and countersink so that the depth of the countersunk portion was between 1/32" and 1/16". For each bolt, 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. Thus, 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 mot be damaged during the impact bolting procedure. 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.

2.3 Description of Equipment Used

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. 1) 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 calibrater (14) was used to measure internal tension in the torqued calibration series of tests. In actual field procedure a bolt is inserted in the device, being held in place by changeable bushings and plates so that one calibrator can be used to adjust wrenches on a number of different bolts sizes. Tightening the nut transmits pressure through the hydraulic load cell to a calibrated gage indicating bolt tension in pounds.

When the turn-of-nut method is used to install bolts, the Skidmore-Wilhelm device is necessary only for calibrating manual torque wrenches used for inspection purposes and to insure that the required amount of turn is obtained in a reasonable period of time.

Figure 2 is a photo of the Skidmore-Wilhelm calibrator used in the torqued calibration tests. To accommodate the C-frame extensometer used to measure elongation 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 testing machine before and after testing. (Fig 3) From the resulting calibration curve it was evident that for this particular Skidmore-Wilhelm calibrator the 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 4 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. Lingle bolts were pulled in tension in a testing machine while elongations were read using the C-frame extensometer. Figure 5 is a typical view of a bolt as it was being tested.

The procedure for obtaining a direct tension vs. elongation curve was as follows: The bolt to be calibrated was selected and centerdrilled. It was then inserted in the special tension grips in the testing machine and the position of the testing machine head set so that, at the required grip, the nut was only finger tight and the bolt was unstressed. Zero readings of 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 prood load. At this point load was removed in increments to zero. The bolts were then measured a second time at zero load to insure that the permanent elongation did not exceed the specification maximum of .0005". Having checked the proof load requirements, testing was resumed in similar increments of load while in the elastic range; elongation increments were used throughout the generally flat strain hardening range.

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. This load was chosen to simulate the "snug" position of the turn-of-nut method. Through experience this simulated snugging tension was adopted as being a good approximation of the tension induced during the rather arbitrary snugging operation. Using an impact wrench, the nut was rotated in 45 degree increments of turn. Load and elongation readings were recorded at each increment until failure occurred or until failure was imminent.

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 in the field. After all load had been removed, the snugging load was reapplied and the nut was once more rotated through one-half turn. 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 throughout and furnished a complete test history.

This same procedure was used to test a second bolt from the same lot except that, in this test, one complete turn of nut was used rather than one-half. Again, a complete history of the test was recorded.

4. TEST RESULTS

A total of 110 bolts were calibrated. These represent thirteen 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 minmum strength specified by ASTM- A 325. Bolts of the Q-W lots inclusive were actually from the same lot insofar as steel and head treatment were concerned, but they were given different letter designations because of the different lengths of bolts and of thread. The Q-W bolts had cut threads while all other bolts had rolled threads.

Figure 6 is a table showing the results of the entire bolt calibration study including direct tension and torqued calibration control tests on each lot of bolts. Typical direct tension and torqued calibration curves of tension vs. elongation for the three size bolts included in this study are shown in Fig. 7. and Fig. 8 respectively.

In addition to the test results shown in Fig 6, single B-lot bolts were tested at grip lengths of 3 5/8" and 3 1/2" so that the lengths of thread in the grip were 1/4" and 1/8" respectively. For the 3 5/8" grip bolt ultimate load was 49.5^k while rupture occurred at an elongation of .16"; for the 3 1/2" grip bolt, ultimate load was 47.5" while rupture occurred at an elongation of .15".

5. ANALYSIS OF RESULTS

5.1 Direct Tension vs. Torqued Calibration

Figure 9 is a typical curve comparing the load-elongation properties of direct tension and torqued calibration for 7/8" B-lot bolts. In this, and all other lots of 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 strength is apparent. The difference in ultimate strength 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 turning of the nut to produce failure reduces the amount of tension that can be developed in comparison with that developed by a direct tensile load. The apparent reduced strength 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 from 4 inches to 6 3/4 inches (lot 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. 10 at 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. 6). 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 essentially 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 direct relationship between grip length and elongation no longer holds true with loads greater than the proportional limit.

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. 11). Notice in the photo (Fig. 12) 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. In the torqued calibration tests involving thread length effects, single B-lot bolt tests with 1/4" and 1/8" of exposed thread in the grip were superimposed on the torqued calibration curves of the Q, R, and S lots (Fig. 13) to determine whether small lengths of exposed threads will effect the tension-elongation turn of the nut relationship sufficiently to limit the application of the turn-of-nut method. From the resulting curve it is evident that with as little as 1/8" of thread in the grip, maximum elongations of approximately 0.14" were obtained at 1 7/8" turn-of-nut. By way of comparison, bolts with 3/4" of thread in the grip fracture at from 2 to 3 turns from snug.

The points marked on the curves at approximately .025" elongation indicate one-half turn-of-nut from snug and illustrate the margin of safety against rupture for bolts having varied amounts of thread in the grip. Since the direct tension ultimate strength of the B-lot was approximately the same as that of the Q, R and S lots, these curves may be compared directly.

5.4 Evaluation of Turn-of-Nut Procedure

In standard erection procedures the bolt tension can be 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 14 is a curve constructed from the data obtained by torquing several Z-lot bolts continuously to 1/2 turn, 1 turn and 1 1/2 turn respectively from the "snug" position. These points were located 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. Notice that the turn-of-nut procedure 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 proof load. In fact, for this particular lot of bolts, the tension induced by the one-half turn-of-nut mtehod was approximately 30% greater than the specified proof load.

The one turn-of-nut zone falls approximately 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 15 is a bolt tension distribution chart plotted for six bolted butt joints tested at Lehigh University (7). Information gathered in this calibration study was used to plot the average tension-elongation curve. 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 elongation results in relatively small variation 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 (12) 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 16 is a plot of tension expressed as a per cent of proof load 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 112% of proof load. Moreover, it was found that the average percentage of proof load at 1/2 turn-of-nut for all grips tested was 115%. For general interest the same comparison was made at 3/4 turn-of-nut. In this case the average internal tension for all grips was 130% of proof load. Ultimate load, occurs at approximately 141% of proof load. These figures indicate that the portion of the turn-of-nut method controlling the increased amount of rotation for 7/8" bolts having grips of greater than 5" is conservative. All bolts used in these comparisons were from the same heat as well as heat treatment and exhibited similar material properties. The snugging tension was 8^k. Measurements of bolts in an 8 ply structural joint after snugging have shown internal tensions to be as great as 15^k (Fig. 17). These facts illustrate that 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:

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

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 the 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 18 is a non-dimensional plot of induced tension at any particular turn-of-nut (Ta) 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. 9) 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 3.3. 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 for any simulated number of installations 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 installed according to the one-half turn-of-nut procedure 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" under head.

1. When internal tensions are induced in a bolt by turning the nut against the resistance of the gripped material, both the ultimate strength and the 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 beyond the proportional limit of the bolt (Fig.10,16)
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 (Fig. 11, 12, 13).
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 more than it need be; it is not, however, detrimental to the performance of bolts installed according to this recommendation (Fig. 14,15,16,17,18).

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 previously have been properly installed according to the one-half turn-of-nut procedure as long as the same turn-of-nut is used for subsequent installations. For erection purposes bolts installed in this way can be re-used as often as five times without reaching ultimate and still have a factor of safety against rupture of approximately 2 (Fig. 17,18).

Comment on less than 10% difference at working range

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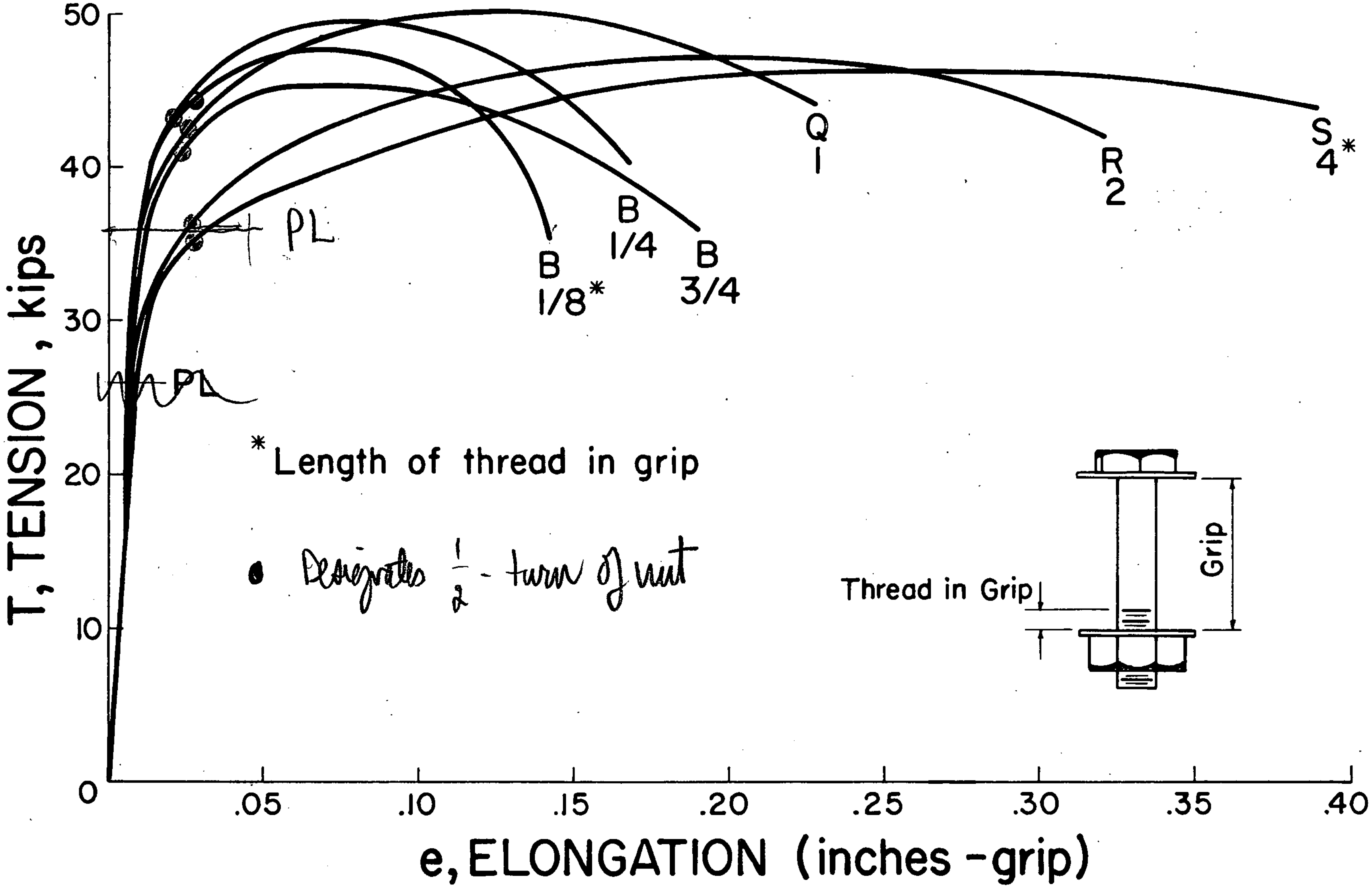

Fig. 18 — Torqued

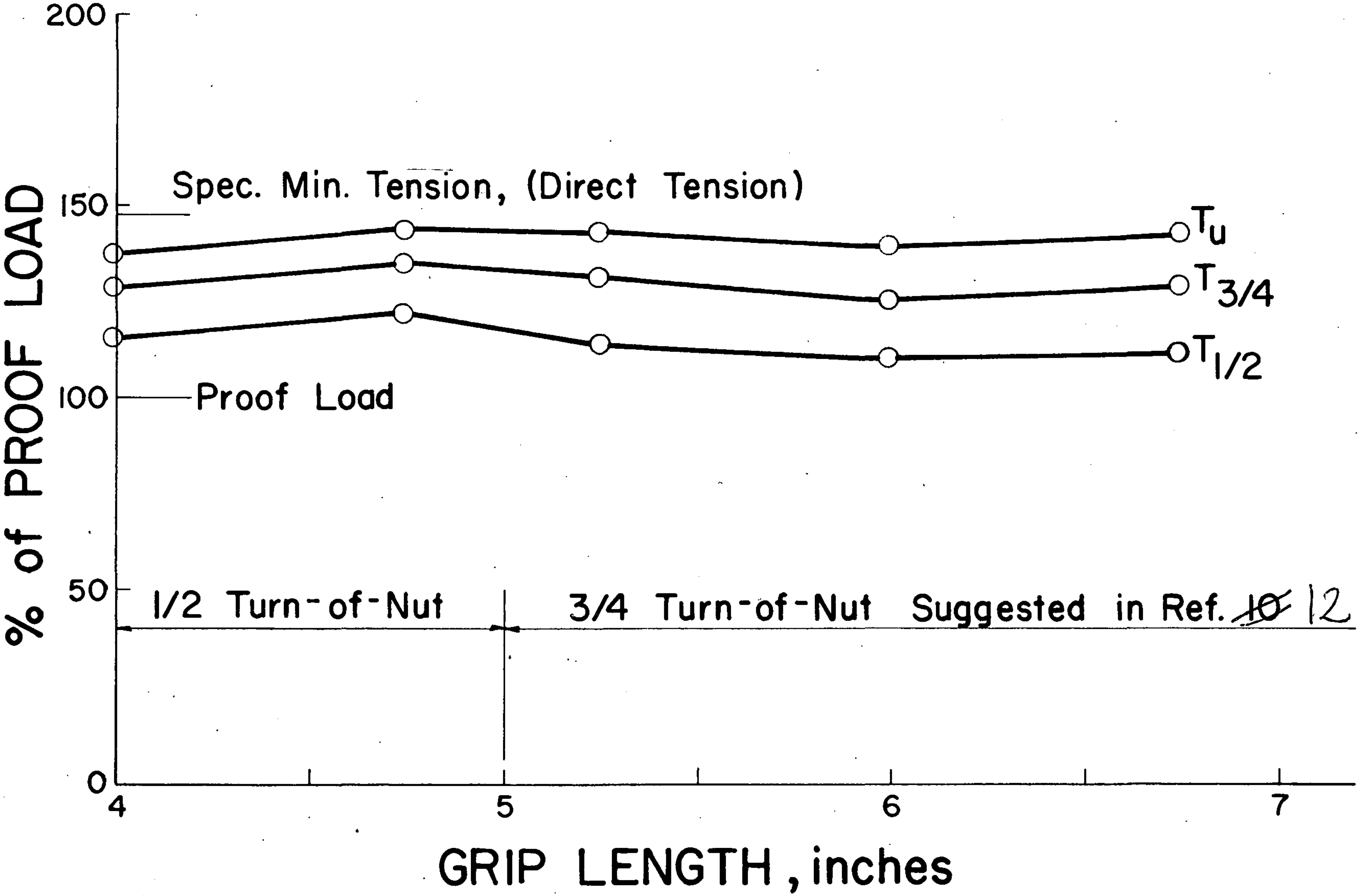
200
150
100
50
0
4
5
6
7
% of PROOF LOAD
GRIP LENGTH, inches
Spec. Min. Tension, (Direct Tension)
Proof Load
T_u
$T_{3/4}$
$T_{1/2}$
1/2 Turn-of-Nut
3/4 Turn-of-Nut Suggested in Ref. ~~10~~ 12

Fig. 24