DEPARTMENT OF CIVIL ENGINEERING
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University of Alberta
Department of Civil Engineering

Structural Engineering Report No. 201

STRENGTH AND INSTALLATION CHARACTERISTICS OF TENSION-CONTROL BOLTS

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ABSTRACT

The Research Council on Structural Connections of the Engineering Foundation provides a specification for the installation of high-strength bolts. That Specification is directed primarily at users of ASTM A325 or A490 bolts. The use of so-called *alternative design fasteners* is also permitted, however.

Tension-control bolts are a relatively new type of alternative design fastener. The bolt has a splined end that extends beyond the normal threaded portion of the bolt, and an annular groove is present between the threaded portion of the bolt and the splined end. In order to install these bolts, a special electrically-powered wrench is required. This wrench has two coaxial chucks—an inner chuck that slips over the splined end of the bolt and an outer chuck that envelopes the nut. The two chucks turn relative and opposite to one another to tighten the bolt. At some point, the torque developed by the friction between the nut and bolt threads and at the nut-washer interface equals the shear resistance of the bolt material at the annular groove and then the splined end of the bolt shears off at the groove. If the system has been properly manufactured and calibrated, bolt pretension is achieved at this point.

Factors that control the pretension are material strength, thread conditions (such as lubrication, dirt, and thread damage), the diameter of the splined end, and the surface conditions at the nut–washer–joint interface.

The program reported herein investigated the pretension of production tension-control bolts as it varied from manufacturer to manufacturer and under different conditions of aging, weathering, and thread conditions. Further objectives were to examine the behavior of these bolts in direct and torqued tension and to establish whether or not these bolts meet the material properties requirements of the governing standards.

LIST OF SYMBOLS

AD = bolts as-delivered

D = slip probability factor

k_s = slip coefficient

m = number of slip planes in a joint

n = number of bolts in a joint

N_b = number of bolts in a joint

N_s = number of slip planes in a joint

P_s = slip load of a joint

R_s = slip load of a joint

t = statistical measure of difference between two mean values

T_i = bolt pretension

$T_{i\,spec}$ = specified minimum bolt pretension

T_m = specified minimum bolt pretension

UW2 = bolts stored in a sealed keg in the laboratory for two weeks

UW4 = bolts stored in a sealed keg in the laboratory for four weeks

WC2 = bolts exposed to the weather while snug-tight in a simulated steel joint for two weeks

WC4 = bolts exposed to the weather while snug-tight in a simulated steel joint for four weeks

WK2 = bolts exposed to humidity for two weeks

WK4 = bolts exposed to humidity for four weeks

WL2 = bolts with full exposure to the weather for two weeks

WL4 = bolts with full exposure to the weather for four weeks

α = $T_i / T_{i\,spec}$

μ = mean slip coefficient

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1.0 INTRODUCTION

1.1 GENERAL BACKGROUND

Pretensioned high-strength bolts are required when slip of the joint would produce an unacceptable change in the geometry of the structure, when the joint is subject to load reversals, or when bolts are loaded in direct tension. Typical applications for pretensioned high-strength bolts are for use in a splice in a bridge girder, in a lap splice in a column that must transmit moment, or in a tension hanger joint. In the case of the bridge girder, repeated slip of the joint could lead to fretting fatigue. Slip of a column lap splice would allow rotation, thereby increasing the deflection of the column and producing an increase in the second-order bending effects. It is considered desirable to use pretensioned bolts in connections that are loaded in direct tension so that the parts do not separate at the service load level.

In the case of a slip-critical joint, the capacity of the joint is a function of the slip coefficient of the faying surfaces and the clamping force provided by the high-strength bolts. One of the difficulties in designing this type of joint is that both the slip coefficient and the clamping force are quantities that can have a considerable dispersion about their mean values. Furthermore, while the condition of the faying surfaces may be reasonably apparent from a visual inspection, the pretension of a bolt is not.

The Research Council on Structural Connections provides a specification for the installation of high-strength bolts (1). The Specification requires that the bolt pretension in a slip-critical or direct tension joint be at least 70% of the specified minimum tensile strength of the bolt. The Specification permits the use of four techniques for achieving the required pretension: turn-of-nut installation, calibrated wrench installation, use of load-indicating devices, and, finally, the use of so-called alternative design bolts.

1.2 INSTALLATION METHODS FOR HIGH-STRENGTH BOLTS

1.2.1 The Turn-of-Nut Method

The turn-of-nut method has proven to be a reliable and economical technique for installing high-strength bolts. The method consists of two steps. In the first step, the bolts in the connection are brought to a snug-tight load level. This brings the clamped parts into contact and provides a consistent starting point for further tightening. In the second step, the bolts are given their final pretension by rotating the nut relative to the bolt by a prescribed amount—the amount of rotation necessary is dependent on the ratio of bolt length to bolt diameter. Thus, an elongation is applied in order to achieve the required pretension. The snug-tight load is small compared to the load obtained from the additional turn, and, since the bolt elongation induced by the additional turn is independent of thread conditions (e.g., lubricant, rust, or contamination conditions), the final pretension is virtually independent of the thread conditions.

The RCSC Specification (1) requires that at least three bolts of each length, diameter and grade that are used on the work site be checked in a load-measuring device (e.g., Skidmore-Wilhelm hydraulic load cell). Using the stipulated procedure, these bolts must achieve a pretension that is at least 5% greater than the specified minimum pretension.

On average, the turn-of-nut method gives pretensions of 1.35 when normalized with respect to the specified minimum pretension for A325 bolts (with a standard deviation of 0.12) and 1.26 for A490 bolts (with a standard deviation of 0.10) when these bolts are installed to one-half turn past snug (2). The simplicity and reliability of this method of installation makes it attractive. The main factor governing the bolt pretension is the bolt material strength. Since a bolt with a low ultimate strength will undergo the same nut rotation (fastener elongation) as an identical bolt with a higher ultimate strength, the lower strength bolt will have a smaller pretension.

The main requirements for inspection, as given by the RCSC Specification (1), are to check that all of the plies of the joint are in firm contact with each other and to observe that the installation has taken place according to the procedures specified on the drawings (i.e., turn-of-nut method). The inspector must observe the calibration and demonstration testing. In addition, the inspector must ensure that the components meet the requirements of Sections 2, 3 and 8 of the RCSC Specification. These sections deal with the condition of the bolt assemblies, bolted parts, and the installation and calibration of the bolts. When a disagreement regarding the minimum pretension of the installed bolts exists, the RCSC Specification provides an "Arbitration Inspection" method to check the pretension of the installed bolts. This inspection method uses a specially calibrated torque wrench to check the installed bolts. An inspection method other than the arbitration inspection method may be used if it is approved by the Engineer of Record.

1.2.2 The Calibrated Wrench Method

The calibrated wrench installation is probably easier for the operator than the turn-of-nut installation, but it produces lower and less reliable values of pretension. The method requires that the installation wrench be calibrated for the particular lot of fasteners being installed. A minimum of three bolts of each diameter must be calibrated at least once each working day. Additional calibrations are required whenever a significant change is made in the equipment or when the surface conditions of the nuts, bolts, or washers change. Using a load-measuring device, such as the Skidmore-Wilhelm hydraulic load cell, the air-operated wrench is calibrated to shut off at a bolt tension that is not less than 5% greater than the minimum specified pretension. A hardened washer is required between the clamped material and the turned element to minimize the frictional variation.

Unlike the turn-of-nut method, the pretension here is independent of the bolt material properties. However, the pretension is highly dependent on the friction conditions between the bolt and nut threads and the nut-washer interface. An average normalized pretension of 1.13 with respect to the specified minimum pretension with a standard deviation of 0.06 have been reported (2) for both A325 and A490 bolts. The standard deviation can quickly change, however, as the frictional condition of the bolt, nut, or washer changes. Inspection requirements are the same as in the turn-of-nut method. The calibrated wrench method was excluded from the RCSC Specification between 1980 and 1985, and it is currently not permitted by the Canadian Standard (3).

1.2.3 Direct Tension Indicators

The most common type of direct tension indicator is the load-indicating washer. Installation is done using a special washer that has small protrusions on one face. Pretension is monitored by measuring the size of the gap left as these protrusions deform under increasing bolt load. The gap necessary to achieve the proper pretension is determined by calibration. When placed under the non-turned element, load-indicating washers directly reflect the tension in the bolt, provided they have been calibrated and installed properly. The RCSC Specification requires that load-indicating devices be calibrated. A minimum of three representative direct tension indicators for each bolt diameter and grade are tested using three typical bolts from each diameter and grade in a device capable of measuring the bolt pretension (e.g., a Skidmore-Wilhelm hydraulic load cell). It is required that the bolt assembly be identical to the assembly subsequently used in the actual joint. The calibration must demonstrate that the pretension achieved when using the direct tension indicator is at least 5% greater than the specified minimum pretension. Some further requirements are stipulated, and the RCSC Specification should be consulted.

Since the bolt tension is reflected by the magnitude of the gap, this method will be independent of the bolt material properties and the friction conditions. Of course, if the strength of the bolt is too low to achieve the necessary tension, this will be obvious from the fact that the required gap will not be obtained. Inspection is similar to that required for the turn-of-nut and calibrated wrench methods. (Although the RCSC Specification does not require that the gap be checked for inspection purposes, it is reasonable to expect that this check would normally be carried out.)

1.2.4 Tension-Control Bolts

Tension-control bolts are a relatively new type of alternative design bolt. The bolt itself has a splined end that extends beyond the threaded length of the bolt. It also has an annular groove between the threaded portion of the bolt and the splined end. An illustration of a typical tension-control bolt is given in Figure 1.1. In order to install these bolts, a special electrically-powered wrench is required. This wrench has two coaxial chucks—an inner chuck that slips over the splined end of the bolt and an outer chuck that envelopes the nut. The two chucks turn relative and opposite to each other to tighten the bolt. At some point, the torque developed by the friction between the nut and bolt threads and at the nut-washer interface equals the shear resistance of the bolt material at the annular groove and the splined end of the bolt shears off at the groove. If the system has been properly manufactured and calibrated, pretension is achieved at this point. The installation procedure is relatively independent of operator control, and use of the light-weight electric wrench can be economical as compared with an installation using an air-operated impact wrench. Since the bolt is loaded entirely in direct tension, it should have greater ductility as compared to an A325 bolt installed using the turn-of-nut technique.

Factors that control the pretension are material strength, thread conditions (such as lubrication, dirt, and thread damage), the diameter of the splined end, and the surface conditions at the nut-washer-joint interface. Material strength and splined end diameter aside, two hypothetical extremes can be considered for illustration. At one limit, the friction can be assumed to be very large. In this case, torsion will build up rapidly and the splined end will shear off before any significant amount of pretension is attained. At the other limit, the friction can be assumed to be very low. Since the torsion in the bolt will also be low, the bolt will fail in direct tension before the splined end has sheared off. As illustrated, friction can play a major role in determining the level of pretension achieved.

The RCSC Specification (1) treats alternative design fasteners in a fashion similar to the other installation methods: a minimum of three bolts from each length, diameter and grade must be tested in a load-measuring device, and they must provide a pretension that is at least 5% greater than the specified minimum pretension. Installation of the bolts is to be done according to the manufacturer's instructions. However, recognized procedures for joint installation are still required. Plies must be drawn together in a systematic and, possibly, iterative way before the final tightening, as required with all approved installation techniques, in order to provide a more evenly distributed pretension across the joint. The inspection follows the same procedure as the turn-of-nut method.

1.3 SCOPE

The main purpose of the testing program reported herein was to investigate the pretension of tension-control bolts, not only as it may vary from manufacturer to manufacturer, but under different aging, weathering, and thread conditions. Further objectives were to examine the behavior of the bolts in direct and torqued tension and to establish whether or not these production bolts meet the material properties requirements of the governing standard (4). The results of the tests are used to evaluate the reliability of the bolts for use in high-strength bolting and to set out guidelines for the physical handling and care of tension-control bolts.

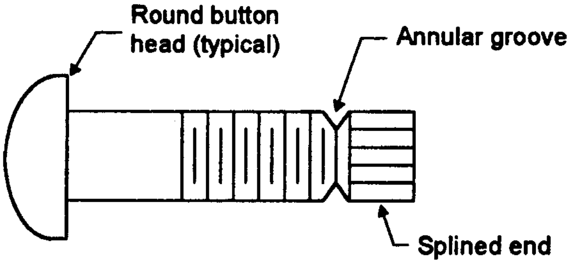


Fig. 1.1. Typical tension-control bolt

2.0 LITERATURE SURVEY

2.1 ESTABLISHED METHODS OF INSTALLATION

As previously noted, the Research Council on Structural Connections of the Engineering Foundation provides a specification for structural joints that use ASTM A325 or A490 bolts (1). This Specification permits four methods for the installation of pretensioned, high-strength bolts. These are: the turn-of-nut method, the calibrated wrench method, the use of direct tension indicators, and the use of alternative design bolts. This Section will review work related to these installation techniques.

2.1.1 The Turn-of-Nut Method

A great deal of the research on the turn-of-nut method (discussed in Section 1.2.1) has been summarized in the *Guide to Design Criteria for Bolted and Riveted Joints* (2). The *Guide* reports on laboratory studies on A325 bolts which indicate that, when installed to one-half turn from snug tight, these bolts will give pretensions of 1.35 with respect to the specified minimum pretension. The accompanying standard deviation is 0.12. However, when A325 bolts are installed to one-third turn from snug tight, the studies showed that the average pretension was only 1.21, standard deviation 0.06.

The measured pretensions are greater than the specified minimum values because both the installation itself provides for more pretension than required with respect to the specified minimum pretension and the bolt strengths generally exceed the specified minimum ultimate tensile strength. Typically, one-half turn from snug will produce a bolt tension that is 80% of the specified minimum ultimate tensile strength, which is greater than the 70% required by the RCSC Specification (1). As reported in the *Guide*, the average strength of A325 production bolts is 18.3% greater than the specified minimum ultimate strength. Thus, the combination of bolts stronger than required installed to a pretension that is higher than required gives an actual pretension of (1.183)(80/70) = 1.35 times the specified minimum pretension.

This is illustrated in Figure 2.1. In this figure, load vs. deformation responses are given for two hypothetical bolt lots. Each is loaded by turning the nut. Bolt lot B is stronger than bolt lot A. Because of the difference in bolt strength, application of the same elongation to both bolts (e.g. one-half turn-of-nut) results in a higher bolt tension for bolts from Lot B. Thus, the turn-of-nut method makes use of the strength potential of the bolt being installed. (Also shown in the figure is the bolt tension attained using the calibrated wrench method. This will be discussed later.)

As has been noted, the values cited come from installation tests that were done in laboratories only. More recently, a study was conducted to examine bolt pretensions in the field (5). In this study it was found that the measured average pretension of A325 bolts installed in bridges using the turn-of-nut method was 1.27 with respect to the specified minimum pretension, with a standard deviation of 0.20. In structures other than bridges, the measured pretension was much less, being 1.11, standard deviation 0.15. (This study incorporated both A325 and A490 bolts installed by turn-of-nut, galvanized A325 bolts installed by turn-of-nut, and A325 bolts installed with a load-indicating washer.) It was found that, in many cases, bolt installation was controlled by monitoring the sound of the impact wrench instead of the prescribed procedure of snugging the bolt, marking the required nut rotation, and then turning the nut to that rotation. Of course, installation by "sound" is not a recognized installation technique. Galvanized A325 bolts installed by turn-of-nut had pretensions that were 1.12 with respect to the specified minimum pretension, standard deviation 0.18.

2.1.2 The Calibrated Wrench Method

The *Guide* also provides information on the calibrated wrench method (discussed in Section 1.2.2). An analysis of tests done on both A325 and A490 bolts (2) showed that the average clamping force provided by either grade is 1.13 with respect to the specified minimum pretension, standard deviation 0.06. The standard deviation was found to be dependent on the number of bolts in a joint. As the number of bolts in a joint increases, the standard deviation tends to drop.

The value of 1.13 cited in the *Guide* is taken from bolt tests. However, an illustrative derivation is also provided in the *Guide*. In the derivation, it is assumed that the bolts will be installed to a pretension that is 7.5% greater than the specified minimum pretension. The explanation for this is that most specifications require that wrenches be calibrated to provide a pretension that is either 5 or 10% greater than the specified minimum pretension. Accordingly, the value of 7.5% was selected. It is also assumed that joint installations lead to pretensions that are 5.5% greater than those obtained when bolts are installed in hydraulic calibrators, since hydraulic calibrators are not as stiff as actual joints. Therefore, the value of 1.13 can also be obtained from the calculation: 1.075 x 1.055 = 1.134.

The *Guide* statement that bolt installations in hydraulic calibrators lead to lower pretensions than when bolts are installed in actual joints must be questioned. When a wrench is calibrated, it is set to stall at certain torque, that torque being the one which corresponds to the desired pretension. Regardless of the flexibility of the joint, the wrench will continue to tighten the bolt until the stalling torque is reached.

Joint stiffness might be an issue when using the turn-of-nut method on a joint that is not properly compacted. With the turn-of-nut method, pretension is controlled by imposing a nut rotation, as explained in Section 1.2.1. If a joint is extremely flexible, installing a bolt to one-half of a turn might simply compress the joint without inducing any significant load in the bolt. A calibrated wrench installation, however, does not stop at a prescribed turn: tightening continues until the stall torque corresponding to the desired pretension is reached.

Unlike the turn-of-nut method, bolt pretensions attained by the calibrated wrench method are independent of the bolt material properties, but they are highly dependent on the friction conditions of the bolt assembly. These friction conditions are rust, lubrication, and dirt contamination on the bolt threads, nut threads, or the washer. Also included within the friction conditions are thread matting and thread damage. Since a calibrated wrench will stall at a preset torque that is determined by calibration on a sample of bolts, the actual installed pretension of any given bolt will depend on how similar its friction conditions are to those of the bolts used in the calibration. For example, if the bolts used in calibration have very low frictional resistance, the preset torque will be low. If the wrench is then used to install bolts with a higher frictional resistance, the preset torque will likely not be large enough to provide the required pretension.

Figure 2.1 shows the bolt pretension obtained by using the calibrated wrench method on bolts from different lots, one with a higher ultimate strength than the other. (Also shown in this figure are pretensions obtained using the turn-of-nut method.) Despite the difference in ultimate strength, the pretension for the two lots is identical. (It is assumed that the friction conditions of the two bolts are also identical.) This is because the wrench uses quasi-load control to obtain pretension.

2.1.3 Direct Tension Indicators

The most common type of direct tension indicator is a load-indicating washer (discussed in Section 1.2.3). The pretension provided in a bolt assembly that uses these washers is reported to be 1.03 with respect to the specified minimum pretension when A325 and A490 bolts are installed in a hydraulic calibrator with parallel surfaces (6). (A standard deviation is not reported.) When the bolts were installed in simulated joints, the pretension rose sharply, to 1.17. (It should be noted that this information is not given explicitly in the reference, and some numerical manipulation is required.) In the case of the simulated joints, bolt tensions were determined by measuring bolt elongations and relating them to bolt loads by means of a load vs. deformation relationship. No explanation for the difference in pretension as attained from the hydraulic calibrator and from the test joints is given in Reference 6.

Field measurements of 60 A325 bolts installed with a load-indicating washers (5) showed that the average pretension was 1.12, standard deviation 0.13.

With load-indicating washers, bolt tension is monitored solely by the gap between the protrusions on the load-indicating washer and the gripped material. This is not affected by the material properties of the bolt, variation in friction, or grip length. Provided that the load-indicating washer is properly calibrated, any variation of the indicated pretension from the true value will be the result of manufacturing tolerances on the washers, seating of the washer relative to the bolt, and the skill of the operator in determining the size of the required gap.

2.2 TENSION-CONTROL BOLT STUDIES

There is very little literature available on the behavior of tension-control bolts. Of the few reports available, most were sponsored by companies involved in tension-control bolt manufacturing.

2.2.1 Lehigh University Report

A test program was undertaken at Lehigh University (7) in 1979 on behalf of the T.C. Bolt Corporation. The test program involved measuring the slip load of three joints made from ASTM A36 steel and which used 7/8 in. diameter A325 tension-control bolts in short slotted holes without washers under the head of the bolts. Three bolts were first tested in a Skidmore-Wilhelm hydraulic bolt calibrator, and the pretensions obtained at twist-off of the splined extension were 40.5, 41.0, and 41.5 kips (180.2, 182.4 and, 184.6 kN). The average is 41.0 kips (182.4 kN). The specified minimum pretension for a 7/8 in. A325 bolt is 39 kips (174 kN). Therefore, the average pretension measured was 1.051 with respect to the specified minimum pretension. The predicted slip load was calculated to be 104.8 kips. This was based on an assumed pretension of 39 kips for each bolt and an assumed coefficient of friction of 0.336 for the connected material.

Testing the joints in tension yielded actual slip loads of 118.5, 146.0, and 123.0 kips (average 129.2 kips). Thus, the average slip load was 23% greater than the slip load predicted on the basis of the assumptions just described. The difference between the actual slip load and the predicted slip load was assumed to be due, at least partly, to the fact that the test joints are stiffer than the hydraulic calibrator which allowed for higher bolt pretensions. This is not reasonable.

Tension-control bolts use a form of torque control to achieve pretension. As explained in Section 2.1.2, joint stiffness does not affect pretension when bolts are installed by measuring torque (either directly, or in the case of tension-control bolts, indirectly). The difference between the calculated slip load of 129 kips and the values measured in the tests is more logically explained on the basis that (a) the slip coefficient assumed for the steel is too conservative and (b) slip load results generally show a high scatter. For example, if the slip coefficient was, in fact, one standard deviation higher (i.e., 0.336 + 0.07 = 0.406), then the predicted slip load would be 133 kips, which is reasonably close to the average slip load of 129.2 kips. (The average bolt tension of 41.0 kips is used in this calculation.) Since the slip coefficient for the steel that made up the joints was not obtained in an independent way, the matter of just what the actual bolt tension was cannot be resolved.

In another, related, report from Lehigh University (8), the behavior of tension-control bolts loaded in torqued tension is examined. In this case, two bolts were tested in torqued tension and two were tested in direct tension.

The bolts used were originally 7/8 in. diameter by 3 in. long A325. Testing bolts of this size in direct tension was not possible, and the shanks of all four were therefore machined to a 5/8 in. diameter. Elongations for the torqued tension test were obtained by measuring nut rotations and relating the rotations to elongations through the thread pitch and a load–compression calibration. This load–compression calibration presumably takes bolt and joint deformations into account.

In the first test, instrumentation was removed early, so that ultimate loads and their corresponding deformations are not available. The load vs. deformation plot of the data that are available shows that the torqued tension response deviates somewhat from the direct tension response. Also, in both the direct and torqued tension response, the data do not appear to fit a smooth curve very well.

In the second test, more readings of load and elongation were taken. The bolt tested in direct tension reached an ultimate load of 44.1 kips (196.2 kN) and the one tested in torqued tension had an ultimate load of 43.5 kips. The direct tension test data do not follow a reasonable curve. Also, the direct tension test ultimate load from the first and second test were not static loads.

There are not enough tests in either of the Lehigh reports to support any conclusions. However, the author claims that the bolts exhibit a direct tension behavior when loaded in torqued tension and that ductility is not compromised since the shank does not carry any shear stresses. Furthermore, they suggest that the pretension of tension-control bolts may be higher in a steel joint as compared to a hydraulic calibrator.

2.2.2 Pittsburgh Testing Laboratory Report

The Pittsburgh Testing Laboratory conducted a test series that involved standard A490 bolts, tension-control A490 bolts, and direct tension indicators (9). Only the tension-control bolts will be discussed here. The bolts were 1 in. diameter with lengths of 3-1/4 or 3-3/4 in. All bolts were tested either after indoor storage of eight weeks or after two weeks of weathering. The age of the bolts upon receipt was not provided.

Of the ten bolts that were tested after indoor storage, only two reached or exceeded the specified minimum pretension. The average pretension was 0.93 with respect to the specified minimum pretension, standard deviation 0.087. It was noted that after eight weeks of indoor storage the bolt threads had become dry.

Four bolts were weathered outside for two weeks after delivery. Two of these bolts achieved an average pretension of only 0.391. The other two were therefore re-lubricated with wax before being tested. Re-lubricating allowed the pretension ratio to rise to 0.922.

2.2.3 Studies of LeJeune Tension-Control Bolts

The LeJeune Bolt Company sponsored a test series aimed at investigating the behavior of their tension-control bolts (10). The test program involved a number of test variables, but only pretension will be discussed herein.

Pretension tests were performed on a total of 24 3/4 and 7/8 in. diameter black bolts and on twelve 7/8 in. diameter weathering steel bolts. The average pretension of these bolts was 1.15, or 15% greater than the specified minimum pretension. These tests were performed in either a solid block or in an hydraulic calibrator. The test results showed that there did not appear to be any difference in pretension as obtained in either of these two devices. The ratio of the average hydraulic calibrator pretension to solid block pretension is 0.998.

Galvanized bolts (24 in total) with diameters of 3/4 and 7/8 in. were also tested. The average pretension was 1.46, normalized with respect to the specified minimum pretension. This high pretension was attributed partly to the special lubricant used on these bolts.

2.2.4 Guide to Design Criteria for Bolted and Riveted Joints

The *Guide* (2) also reports on some tests on tension-control bolts. The bolts tested were A325 bolts with diameters of 3/4, 7/8, or 1 in. The average measured pretension was 1.22 with respect to the specified minimum pretension, standard deviation 0.10. Very few details are provided on the tests and no references are given. It is likely that these bolts were tested in the as-delivered condition.

2.3 CURRENT SPECIFICATIONS

The RCSC Specification (1) provides a design method for slip-critical joints. The equation given to define the slip load of a joint is

$$R_s = D\mu T_m N_b N_s \tag{2.1}$$

where

R_s = nominal slip resistance of the joint

D = slip probability factor

μ = mean slip coefficient of clamped material

T_m = specified minimum pretension

N_b = number of bolts in the joint

N_s = number of slip planes

The mean slip coefficient, μ, has a single value for each of three types of joint surfaces described in the RCSC Specification. The specified minimum pretension, T_m, is equal to 70% of the specified minimum tensile strength of the bolt. The slip probability factor, D, is a multiplier that takes into account the distributions of both the bolt clamping force and the slip coefficient.

The value of D is a direct reflection of the probability of slip of a joint. As D increases for a given value of μ, so does the probability of slip. The RCSC Specification identifies values of D that correspond to a slip probability of 10% when the calibrated wrench method is used to install bolts and 5% when the turn-of-nut method is used. Values of D for other cases are given in the *Guide*.

The nominal slip resistance is multiplied by a resistance factor, ϕ. This resistance factor takes into account the effects of oversized and slotted holes. In both cases, installed pretensions may be reduced (2). Furthermore, in long slotted holes the consequence of slip is much greater and this is reflected in the lower values of ϕ for long slotted holes.

The commentary in the RCSC Specification contains a section that deals with the use of alternative design fasteners. It recognizes that tension-control bolts are subject to most of the variables that affect the calibrated wrench method, but the position taken is that these bolts have good quality control and this may reduce the pretension variability. As will be seen later, the value of pretension is highly dependent on the condition of the bolt lubricant, the amount of rust on the threads and washer, the extent of thread damage, and so on. Depending on how the tension-control bolts perform, the probability of slip may be the same as for the turn-of-nut method, the calibrated wrench method, or some other value.

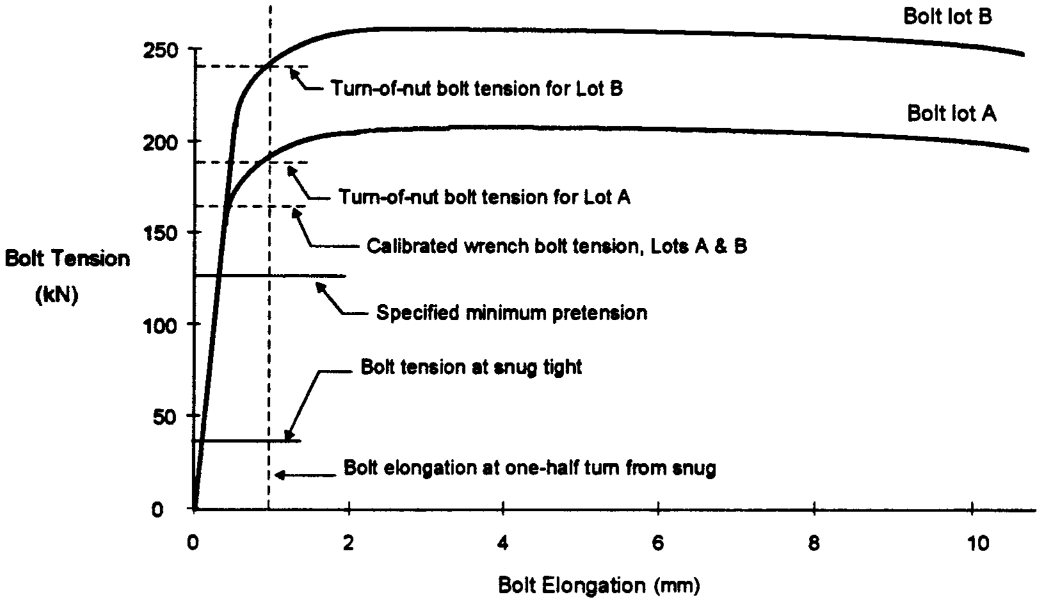


Fig. 2.1. Installed pretensions for different installation methods

3.0 EXPERIMENTAL PROGRAM

3.1 SPECIMEN DESCRIPTION

Bolts were received from seven manufacturers or suppliers; five were American, one was Japanese, and one was a Japanese company that operates in the United States. In total, there were 13 lots tested. The target fastener was a 3/4 in. diameter by 2-3/4 in. long ASTM A325 bolt. This size was suggested by the sponsor of the program, The Research Council on Structural Connections, as one in common use in fabricated steel construction. Eight of the 13 lots were of this size. Of the other five, four were 3/4 in. diameter with lengths of 2-1/4 in., 2-1/2 in., 3 in. and 3-1/4 in., and one was 7/8 in. diameter with a length of 4 inches. The target age of the bolts was that they be as new as possible. Obtaining newly manufactured bolts was difficult, however, because it was not practical for the manufacturers to produce a keg of bolts just for this program. As a result, the age of the bolts varied from approximately one month to two years. The suppliers, bolt sizes, quantities, production dates, and dates of receipt are given in Table 3.1. Suppliers or manufacturers are not identified by name, however.

3.2 SCOPE

3.2.1 Bolt Pretensions

The focus of the program was to measure bolt pretension for tension-control bolts installed in the standard way. Bolts were tested under various conditions of exposure to the atmosphere as well as under different conditions of thread lubrication, contamination, and damage. Exposure periods were two weeks and four weeks. These time periods, although somewhat arbitrary, would likely reflect site conditions. It was the opinion of a local erector that a keg of bolts would not last for more than four weeks on a construction site, and would probably be used up much sooner.

3.2.2 Bolt Material Properties

Tests for material properties were required for a number of reasons. First, it was necessary to confirm that these bolts met the strength and hardness requirements of the ASTM A325 specification (4). Second, the ductility of these bolts in torqued tension is of interest. Since tension-control bolts are loaded completely in direct tension during the normal tension–

control bolt installation, tension-control bolts should display higher ductility as compared to a regular bolt, which is loaded in combined torque and direct tension by conventional (e.g., turn-of-nut) installation methods. Finally, the ultimate tensile strength of the individual lots was desirable in order that the pretension results could be normalized.

3.2.3 Testing Regimen

A typical testing regimen consisted of the following:

- Five bolts tested for hardness (Rockwell C) and direct tension characteristics.
- Five bolts tested for torqued tension characteristics.
- Nine bolts tested for pretension in the as-delivered condition.
- Nine bolts tested for pretension after aging in a sealed keg in the laboratory for two weeks.
- Nine bolts tested for pretension after two weeks of exposure to outside humidity.
- Nine bolts tested for pretension after weathering for two weeks with full exposure to the elements.
- Nine bolts tested for pretension after weathering for two weeks in a joint with full exposure to the elements.
- Nine bolts tested for pretension after aging in a sealed keg in the laboratory for four weeks.
- Nine bolts tested for pretension after four weeks of exposure to outside humidity.
- Nine bolts tested for pretension after weathering for four weeks with full exposure to the elements.
- Nine bolts tested for pretension after weathering for four weeks in a joint with full exposure to the elements.

The numbers actually tested varied somewhat from lot to lot, depending on the number of specimens available in total in each lot. As will be described later, the pretensions were measured either in a solid block using a Lebow load cell, or in a Skidmore-Wilhelm hydraulic calibrator.

Most of the bolt lots were exposed to the weather during the month of September, but Lots 6, 7, 8 and 9 received their exposure during the months of July and August. Furthermore, Lot 13 was exposed during February. The actual dates for the exposure periods are given in Table 3.2.

3.2.4 Bolts Subjected to Various Conditions of Exposure

Bolts from each lot were tested upon arrival of the bolt lot to obtain the "as-delivered" pretension. The results obtained here could then be used as a basis to compare with other tests. Further tests were then performed on bolts from the same lots but which had aged in a sealed keg in the laboratory environment in order to determine whether or not there was any tendency for the thread lubricant to deteriorate with time. Storage such as this is quite likely to occur. For example, one of the lots received was already over two years old.

Other bolts from each lot were subjected to the ambient outside humidity, but protected from direct contact with rain water, in order to determine the effect of humid storage. This was considered to be representative of field storage conditions where the bolts may be stored in a shed but without a lid on the keg.

Some of the bolts from each lot were given direct exposure to all of the atmospheric weathering elements (precipitation, humidity, wind and temperature). Again this could be a possible field condition if bolt are left out in the open.

Often, during erection the erector will initially install bolts in a connection only to a snug-tight condition. He will then move to another area of the structure to do other work, and, after a certain period of time, will return to perform the final tightening. For this reason, the weathered joints tests were established. The joints consisted of a three-plate assembly in which bolts were brought to snug-tight and then the joint was put out to weather in direct exposure to the elements. After various periods of time, the final installation of the bolts was then completed.

3.2.5 Bolts with Various Bolt Thread and Washer Friction Conditions

Specific tests were also carried out to determine the effect of various thread conditions. These thread conditions included:

(a) threads, washers, and nuts in the as-delivered condition

(b) threads, washers, and nuts cleaned with mineral spirits to remove all the lubricant

(c) threads, washers, and nuts cleaned with mineral spirits to remove all the lubricant and then re-lubricated with a multi-purpose lithium grease

(d) threads, washers, and nuts cleaned with mineral spirits to remove all the lubricant and then re-lubricated with a multi-purpose lithium grease on the washer only

(e) threads, washers, and nuts cleaned with mineral spirits to remove all lubricant and then re-lubricated with a thread compound

(f) threads, washers, and nuts cleaned with mineral spirits to remove all lubricant and then re-lubricated with a thread compound on the washer only

(g) threads, washers, and nuts contaminated with sandy soil

(h) threads contaminated with sandy soil (without the nut or washer on the bolt).

In each of the cases listed above, ten bolts were tested and they all came from Lot 1. The purpose of testing bolts that had been cleaned with mineral spirits was to determine to what degree the lubricant governs the pretension. Re-lubricating with lithium grease or thread compound was necessary so that if the bolts did dry out after a period of storage on a construction site, it would be known whether or not they could be brought back to their original quality with respect to the pretension. The reason for testing bolts that were cleaned with mineral spirits with only the washer re-lubricated (with either lithium grease or thread compound) was to assess how much of the frictional torque comes from the nut–washer interface and how much comes from the interface of the nut and bolt threads.

It can be expected that bolts may be contaminated with dirt on a construction site, and it would be reasonable to expect that this contamination will have an effect on pretension. Therefore, bolts contaminated in this way were considered in this program.

Finally, the effect of thread damage was considered. Nine bolts from Lot 2 were tested in the as-delivered condition while another nine, also from Lot 2, were subjected to intentional thread damage and then tested. It is reasonable to expect that bolts could be treated in a rough manner by an erection crew. Also, mistreatment of bolts possibly could occur in the shipping process.

3.3 TEST SET-UP and APPARATUS

3.3.1 Load Measurement

Tests for pretension were performed in either a solid block, using a hollow (3/4 in. inner diameter) Lebow load cell, or in a Skidmore-Wilhelm hydraulic bolt calibrator. The solid blocks consisted of three plies, fabricated from CSA G40.21-M 300W (specified minimum yield strength of 300 MPa) steel and proportioned to be reasonably representative of a symmetric splice. Each of the blocks was 4 in. by 4 in. and consisted of a central plate of a given thickness and two outer plates of identical thicknesses. Typically, the outer plates were each half the thickness of the center plate so that the cross-sectional area of the central plate was equal to the combined area of the two outer plates. Table 3.3 gives the thicknesses of the plates used in each block.

The Skidmore-Wilhelm was equipped with standard bolt head fittings and allowed a grip length of 1-1/4 in. The fittings that are supplied with the Skidmore are capable of accommodating regular hex heads only, and, because most of the tension-control bolts are forged with a round button head, new fittings had to be made. The only difference between the new fittings and the original ones was that the new fittings were machined so as to accept the round head of a tension-control bolt. Tightening of the bolts was done using a standard tension-control bolt electric wrench.

3.3.2 Simulated Steel Joint Apparatus

Plates for the weathered joint tests, shown in Figure 3.1, were fabricated in accordance with the minimum edge and end distances and the minimum spacing requirements of CAN3-S16.1-M89, and the work was carried out by a local fabricator. The thicknesses of the plates were identical to those of the solid blocks (Table 3.3). Two filler plates per bolt were also made, with thicknesses of 5/16 in. and 1/4 in., in order to take up the 9/16 in. thickness of the load cell. All of these plates were sheared and punched except for the 1 in. thick plates which, because of their thickness, required flame cutting and drilled holes. The plates were rectangular, and permitted two rows of five holes, except for lot nine, which had two rows of four holes. The steel used for these plates was CSA G40.21-M 300W.

3.3.3 Torqued Tension Equipment

The torqued tension tests were also performed in the solid blocks (Figure 3.2). Elongations were measured using a linear variable differential transducer (LVDT) mounted in a frame that could be fitted over the bolt (Figure 3.3). The extensometer was designed with a lever arm such that the LVDT experienced three times the amount of elongation of the bolt. This allowed for greater sensitivity and accuracy. Tightening was performed using either a tension-control bolt electric wrench or a long hand-operated torque wrench, depending on whether or not the splined end had sheared off. In order to be able to read the elongation of the bolt both before and after the splined end sheared off, an extension had to be provided. A regular hex nut was modified to slip over the splined end and thread only part way onto the bolt (Figure 3.4). It sat beyond the normal hex nut used to tighten the bolt, and it contained a steel cap and pointer welded to the top. Both the cap and the bolt head had small holes drilled into them to accommodate the pins on the LVDT frame.

3.3.4 Direct Tension Equipment

Direct tension tests were carried out using a compression jig inside a universal testing machine. The jig consists of two loading plates and two loading platforms. An illustration of a loading platform and a loading plate is given in Figure 3.5. The upper loading plate holds the bolt head while the lower loading plate holds the nut. The upper platform passes through the upper loading plate and bears on the lower loading plate while the lower platform passes through the lower loading plate and bears on the upper loading plate. Thus, as a compressive force is applied by the testing machine, the platforms move towards each other. This forces the loading plates to move away from each other and thereby apply a tensile force to the bolt. Elongations were measured using the extensometer device.

3.4 PROCEDURE

3.4.1 Pretension Tests for Bolts Subjected to Various Conditions of Exposure

In all of the pretension tests, the bolts were treated in the same way. First, the bolt was placed in the either the solid block or in the Skidmore-Wilhelm calibrator and the nut was installed to finger-tight. In the case of the solid block, the load cell was present under the bolt head (Figure 3.2). Tightening then proceeded with the tension-control installation wrench in a continuous, one-step process until twist-off of the splined end, thereby establishing the "twist-off" load.

Bolts that were aged in the lab were placed in a metal keg with the lid securely fastened. After the specified amount of time (two or four weeks), the bolts to be tested were removed. The lid was then immediately replaced.

In addition to these short-term indoor storage periods, long-term indoor storage periods were also examined for Lots 1, 10, and 11. Lot 1 was stored for approximately 32 weeks, while Lots 10 and 11 were stored for approximately 24 weeks. After these periods of storage the ages of the bolts were approximately 132 weeks for Lot 1, 46 weeks for Lot 10, and 34 weeks for Lot 11. Lots 1 and 11 were stored as previously described—in a metal keg with the lid securely fastened. Lot 10, however, was stored in a metal keg with the lid only loosely attached so that the bolts were exposed to the environmental conditions in the laboratory.

Bolts that were exposed to humidity were placed in a metal keg with the lid resting on top of the keg and the keg was then placed outside. In this way, the bolts were subjected to the ambient outside conditions but not exposed directly to rainwater. The bolts to be tested were removed at the appropriate time.

The bolts that were to be weathered with full exposure to the elements were laid out flat on a piece of plywood in a location that did not interfere with their exposure. Again, bolts were tested after the specified time period.

In the weathered joint tests, any burrs present were ground off the joint plates and the filler plates, and a wire brush was used to remove any loose mill scale. Next, the plates were cleaned with a solvent to remove any oil and grease. As-delivered bolts were then placed in the connection with filler plates under the bolt head and then brought approximately to snug-tight (Figure 3.1). The filler plates were a substitute for the load cell so that when the bolts were subsequently tested with the load cell in the grip length, the position of the nut on the bolt would be identical to its position when the joint was being weathered. Silicone was then used to seal potential water entry points created by the presence of the filler plates within the grip length. This was done in order to avoid additional rust accumulating on the bolt or increased surface rusting on the plates because of the entry of water. In this way, the only locations at which water could penetrate the joint were under the bolt head, between the central plate of the joint and the two outer plates, or under the nut. This corresponds to field conditions, that is, a joint made up without the filler plates present. The joints were then placed outside to weather. After the specified period of exposure, the joints were brought inside and a wire brush was used to remove any rust or dirt that had accumulated on the bolt threads between the nut and the splined end. This was necessary to avoid transfer of the dirt or rust to the nut threads since, in the field, the nut would not be removed.

The bolts in the weathered joint tests were installed according to recognized procedures. Monitoring of the bolt pretensions started with the bolt at the middle of the joint and proceeded outwards. With all the bolts snug tight, one was then loosened and removed. The filler plates for this bolt were also removed and the bolt was replaced in the hole with the load cell now present. The bolt was then tightened until twist-off of the splined end. Once the load cell was read, that bolt was removed and the load cell taken off. The filler plates were then refitted, the bolt was put back in the joint and brought to snug-tight. In this way, at any given time all of the bolts in the joint would be snug-tight except for the one that was being tested. In the case of Lot 9, however, the bolts were simply removed and tested in the Skidmore since these bolts would not fit in the load cell and, of course, the joint would not fit in the Skidmore.

In all of the pretension tests, the bolts were visually examined for conditions of lubrication, rust and damage. An index system (ranging from 0 to 3) was set up to describe the bolt condition. The number 3 meant that a great deal of lubricant, rust, or damage was present, and the number 0 meant that none was present. From these three indices, an overall friction index can be derived. This friction index is equal to the lubrication index minus each of the rust and thread damage indices. The highest friction index possible is a value of 3—corresponding to a lubrication index of 3 while the rust and lubrication indices are both zero (3 – 0 – 0 = 3). This represents a low coefficient of friction on the bolt. The lowest friction index possible is – 6, corresponding to a lubrication index of 0 with rust and thread damage coefficients of 3 (0 – 3 – 3 = – 6). However, as will be seen later, all of the bolts tested fell between these two extremes.

3.4.2 Pretension Tests for Bolts with Varying Thread and Washer Friction Conditions

In order to study the effects of lubrication, 80 bolts were taken from Lot 1. Ten of the bolts were tested as-delivered. Fifty were cleaned (threads, washers, and nuts) with mineral spirits to remove the lubricant and then allowed to dry. From this 50, ten were tested dry, ten were tested with a multi-purpose lithium grease and the other ten were tested with thread compound that conformed to API Bulletin 7A1 (11). The lithium grease or thread compound was applied liberally to both the bolt threads and to both sides of the washer in this case. Another ten from this lot of 50 had lithium grease applied only to the washer. Similarly, another ten had their washers only lubricated with thread compound. The remaining twenty of the 80-bolt lot were contaminated with soil. A mixture of approximately 70% organic top soil and 30% sand was used. Ten bolts were dropped from waist height (approximately 3-1/2 feet) into the soil and then tested. The other ten were also dropped in the soil, but in this case the nuts and washers were removed first. In both cases, the bolts were then tested without cleaning the threads.

Bolts were intentionally damaged by dropping a metal keg containing 125 bolts (from Lot 2) three times from a height of 2-1/2 feet and rolling the keg on its side for 20 feet. This was considered to be representative of the normal handling of a keg of bolts in the shipping and construction phases. Ten of the 125 bolts were then tested. (The 125 bolts originally consisted of 250 bolts in a keg which appeared to have been damaged in the shipping process.)

3.4.3 Torqued Tension Tests

The torqued tension tests were performed by first tightening the bolt with the electric wrench and then, after the splined end sheared off, using a long hand-operated torque wrench to complete the test. The bolt head was held with a pair of vice grips to keep the bolt from rotating. After tightening the bolt a certain amount, the nut extension was installed and load and elongation measurements were taken. The nut extension was then removed and the bolt was tightened further, and the process then repeated. Five bolts were tested from each lot.

3.4.4 Hardness and Direct Tension Tests

Rockwell C hardness tests were performed on a sample of bolts from each lot in accordance with the requirements of ASTM standards E18 (12) and F606 (13). The tops of the bolt heads were wet-ground to provide a clean, even surface for testing. A very small amount of material was removed in this process. For each bolt, a minimum of five hardness measurements were taken. These same bolts were then subject to direct tension tests.

Direct tension tests were performed in a tension jig with an extensometer attached (Figure 3.5). Tests were conducted according to ASTM specification F606 (13). The loading was performed under stroke control at a constant strain rate. Three static load readings were taken for each bolt tested. Testing was carried out to fracture of the bolt.

Table 3.1
Bolt Lot Information

Manufacturer	*Lot Number*	*Bolt Size (diameter x length, inches)*	*Quantity Supplied*	*Production Date (d/m/y)*	*Date Received (d/m/y)*	*Age Upon Receipt (months)*[3]
A	2	3/4 x 2-3/4	250	22/05/92	21/08/92	3
B	3	3/4 x 2-3/4	75	20/11/90	20/08/92	21.5
	4	3/4 x 2-3/4	75	20/11/90	20/08/92	21.5
	5	3/4 x 3-1/4	120	13/03/92	24/08/92	5.5
C	1	3/4 x 2-3/4	130	28/02/90	28/08/92	30.5
	6	3/4 x 2-3/4	250	28/02/90	26/06/92	28.5
	7	3/4 x 3	130	21/02/92	26/06/92	4
	8	3/4 x 2-1/4	125	Note 1	26/06/92	unknown
	9	7/8 x 4	59	Note 1	26/06/92	unknown
D	10	3/4 x 2-3/4	125	17/06/92	24/08/92	2.5
E	11	3/4 x 2-3/4	125	20/03/92	24/08/92	5
F	12	3/4 x 2-3/4	100	Note 2	25/08/92	unknown
G	13	3/4 x 2-1/2	125	15/01/93	25/01/93	0.5

[1] Mill certificates were not available for this lot so the production date is not certain. However, the supplier estimated that the lot was about two years old.

[2] Mill certificates were not available for this lot. Bolt lubrication appeared satisfactory, however.

[3] Ages are rounded to the nearest half-month.

Table 3.2
Exposure Dates for the Pretension Tests (d/m/yr)
(see legend below for abbreviation meanings)

Bolt Lot	*Start/Test Date*	*AD Test*	*UW2 Test*	*UW4 Test*	*WK2 Test*	*WK4 Test*	*WL2 Test*	*WL4 Test*	*WC2 Test*	*WC4 Test*
1	Start Date	–	10/09/92	10/09/92	10/09/92	10/09/92	10/09/92	10/09/92	10/09/92	10/09/92
	Test Date	31/08/92	24/09/92	08/10/92	24/09/92	08/10/92	24/09/92	08/10/92	24/09/92	08/10/92
2	Start Date	–	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92
	Test Date	31/08/92	22/09/92	06/10/92	22/09/92	06/10/92	22/09/92	06/10/92	22/09/92	06/10/92
3	Start Date	–	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92
	Test Date	26/08/92	22/09/92	06/10/92	22/09/92	06/10/92	22/09/92	06/10/92	22/09/92	06/10/92
4	Start Date	–	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92
	Test Date	26/08/92	22/09/92	06/10/92	22/09/92	06/10/92	22/09/92	06/10/92	22/09/92	06/10/92
5	Start Date	–	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92	08/09/92
	Test Date	26/08/92	22/09/92	06/10/92	22/09/92	06/10/92	22/09/92	06/10/92	22/09/92	06/10/92
6	Start Date	–	–	10/07/92	–	09/07/92	–	09/07/92	–	07/07/92
	Test Date	–	–	07/08/92	–	06/08/92	–	06/08/92	–	04/08/92
7	Start Date	–	–	10/07/92	–	11/07/92	–	11/07/92	–	09/07/92
	Test Date	–	–	07/08/92	–	08/08/92	–	08/08/92	–	06/08/92
8	Start Date	–	–	08/07/92	–	10/07/92	–	10/07/92	–	07/07/92
	Test Date	–	–	05/08/92	–	07/08/92	–	07/08/92	–	04/08/92
9	Start Date	–	08/07/92	08/07/92	11/07/92	11/07/92	11/07/92	11/07/92	09/07/92	09/07/92
	Test Date	08/07/92	22/07/92	05/08/92	25/07/92	08/08/92	25/07/92	08/08/92	23/07/92	06/08/92
10	Start Date	–	09/09/92	09/09/92	09/09/92	09/09/92	09/09/92	09/09/92	09/09/92	09/09/92
	Test Date	26/08/92	23/09/92	07/10/92	23/09/92	07/10/92	23/09/92	07/10/92	23/09/92	07/10/92
11	Start Date	–	09/09/92	09/09/92	09/09/92	09/09/92	09/09/92	09/09/92	09/09/92	09/09/92
	Test Date	27/08/92	23/09/92	07/10/92	23/09/92	07/10/92	23/09/92	07/10/92	23/09/92	07/10/92
12	Start Date	–	10/09/92	10/09/92	10/09/92	10/09/92	10/09/92	10/09/92	10/09/92	10/09/92
	Test Date	27/08/92	24/09/92	08/10/92	24/09/92	08/10/92	24/09/92	08/10/92	24/09/92	08/10/92
13	Start Date	–	02/02/93	02/02/93	02/02/93	02/02/93	02/02/93	02/02/93	02/02/93	02/02/93
	Test Date	02/02/93	16/02/93	02/03/93	16/02/93	02/03/93	16/02/93	02/03/93	16/02/93	02/03/93

Abbreviation	*Meaning*
AD	bolts as-delivered
UW2	bolts stored in a sealed keg in the laboratory for two weeks
UW4	bolts stored in a sealed keg in the laboratory for four weeks
WK2	bolts exposed to humidity for two weeks
WK4	bolts exposed to humidity for four weeks
WL2	bolts with full exposure to the weather for two weeks
WL4	bolts with full exposure to the weather for four weeks
WC2	bolts exposed to the weather while snug-tight in a simulated steel joint for two weeks
WC4	bolts exposed to the weather while snug-tight in a simulated steel joint for four weeks

Table 3.3

Plate Thicknesses for the Solid Blocks and Weathered Joints

Bolt Size (inches)	*Center Plate Thickness (inches)*	*Outer Plate Thickness (inches)*
3/4 dia. x 2-1/4 long	1/4	1/8
3/4 dia. x 2-1/2 long	3/8	3/16
3/4 dia. x 2-3/4 long	1/2	1/4
3/4 dia. x 3 long	1/2	5/16
3/4 dia. x 3-1/4 long	3/4	3/8

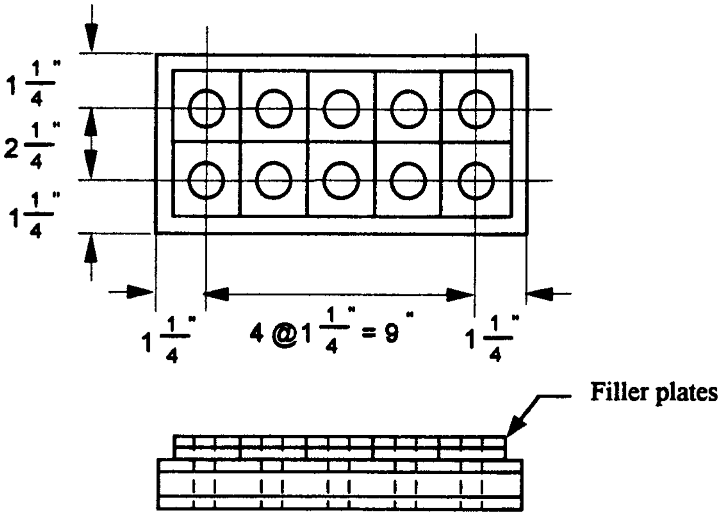


Fig. 3.1 Simulated joint configuration

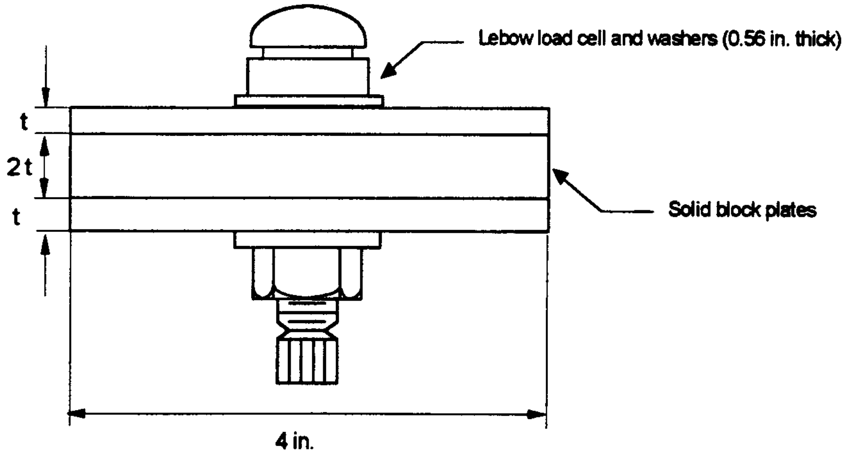


Fig. 3.2 Solid block arrangement

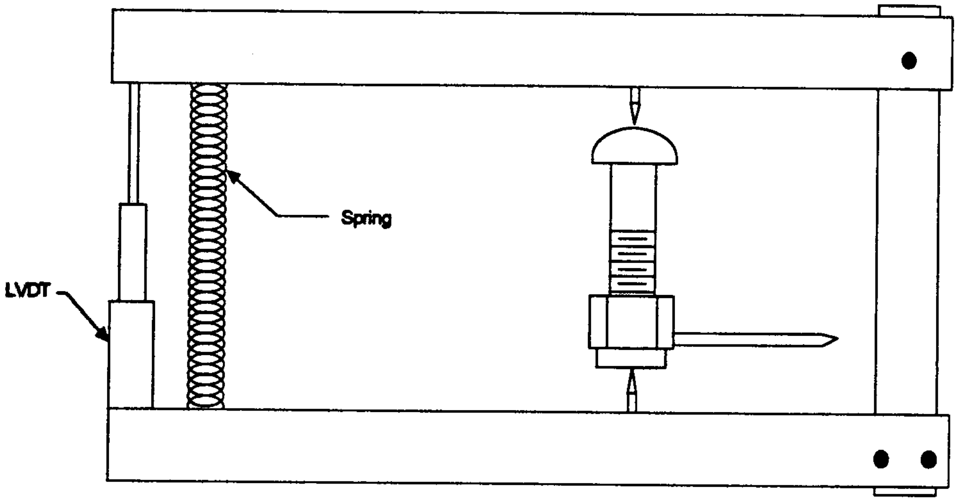


Fig. 3.3 Extensometer arrangement

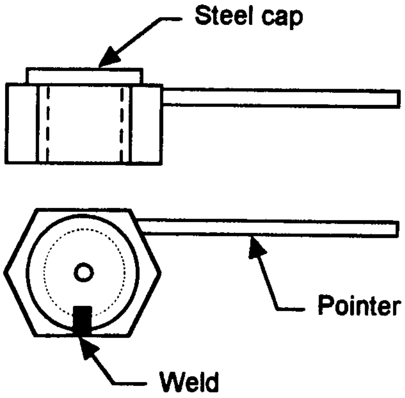


Fig. 3.4 Bolt extension

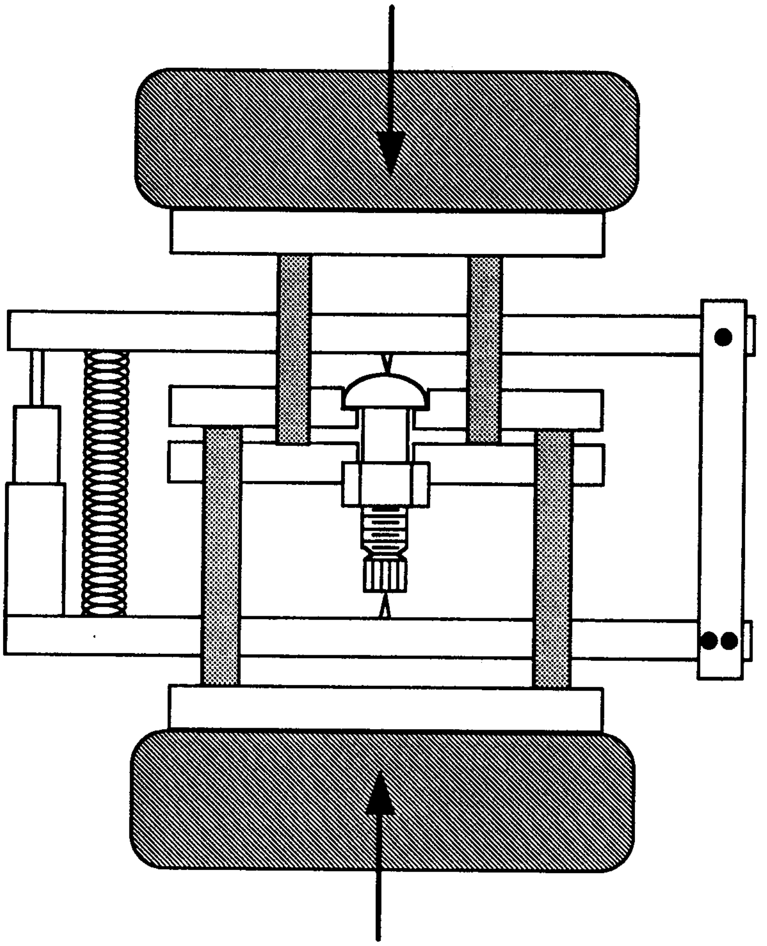


Fig. 3.5 Direct tension set-up

4.0 TEST RESULTS, OBSERVATIONS AND DISCUSSION

4.1 BOLT DIMENSIONS

A summary of the average bolt dimensions and their corresponding standard deviations for the tension-control bolts used in this study is given in Table 4.1. These dimensions are: the bolt head height, the bolt head diameter, the splined end annular groove diameter, and the length of the splined end. Since the customary units of length for structural bolts are inches, these bolt dimensions are also given in inches. Three bolts were taken from each of Lots 1, 2, 5, 10, 11, 12 and 13 as representative of each supplier in this program. For each bolt, one measurement for each dimension was recorded.

The bolt head dimensions are of interest because they identify the bearing surface area against the clamped parts. This bearing surface, which typically is larger for a tension-control bolt head than for a regular A325 bolt head, is intended to keep the bolt from rotating during installation. The diameter of the annular groove at the splined end has a direct impact on the bolt pretension that will be achieved since it reflects the torque that resists the frictional torque. The length of the splined end has an impact on the bolt pretension insofar as it must be long enough to be able to provide adequate shear strength as the wrench is applied. If a splined end is too short, the installation wrench could strip off the splines. This type of behavior was noted in a few cases in this test program.

4.2 BOLT MATERIAL PROPERTIES

The average and standard deviation of the bolt ultimate tensile strength for each of the bolt lots used in this program are given in Table 4.2. Both the average and the standard deviation have been normalized with respect to the specified minimum ultimate tensile strength. Five bolts from each lot were used to determine the lot strength except for Lot 9, where only four bolts were tested because of the limited number of bolts available in that lot. Considering all the lots of 3/4 in. diameter bolts (Lot 9 consisted of 7/8 in. diameter bolts), the average ultimate tensile strength is 214.5 kN, with a standard deviation of 13.0 kN. In terms of stress, these numbers correspond to an average strength of 995 MPa and a standard deviation of 60 MPa. Lot 9 was found to have an average tensile strength of 299.3 kN with a standard deviation of 6.7 kN. If these numbers are divided by the stress area for a 7/8 in. diameter bolt, the strength becomes 1004 MPa, standard deviation

22 MPa. The ASTM specification A325-92a (4) requires that the minimum ultimate tensile strength be 828 MPa. This corresponds to a force of 178 kN for a 3/4 in. diameter bolt and 249 kN for a 7/8 in. diameter bolt.

If results for each of the lots are non-dimensionalized by dividing their measured ultimate tensile strength by the specified minimum ultimate tensile strength, the average value of the ratio is 1.21, with a standard deviation of 0.07. This is reasonably close to the value published in the *Guide* for A325 fasteners (2), namely 1.183, standard deviation of 0.045. The agreement between the measured and published averages and standard deviations implies that the material strength of these A325 tension-control bolts is not significantly different than the material strength of regular A325 bolts, as would be expected. A typical load vs. elongation plot for a tension-control bolt loaded in direct tension is shown in Figure 4.1. (The response in torqued tension is also shown in this figure. This is discussed later.)

Table 4.3 gives the results of the Rockwell C hardness tests done on each lot. The tests were performed on the same bolts used in the direct tension tests described above. For each bolt, a minimum of five hardness readings were taken on top of the bolt head. In cases where there was a significant spread in the readings, additional readings were taken. The overall average and standard deviation for all of the lots combined are 29.4 HRC and 3.2 HRC, respectively. The ASTM specification A325-92a (4) gives the maximum permissible Rockwell C hardness as 34. No minimum hardness is specified. Of all the specimens tested, none had an average hardness that was above 34 HRC. As with the direct tension tests, the hardness tests suggest that the manufacturing of the tension-control bolts used in this program is in accordance with ASTM requirements for A325 bolts.

Table 4.4 reports the ultimate tensile load attained by turning the nut until the bolt failed (torqued tension). This was done by turning the nut with a hand wrench after twist-off of the splined end had taken place during the normal tension-control bolt installation. (See Section 3.4.3.) On average, the torqued bolts were able to reach 88% of the ultimate load that they achieved when loaded in direct tension, with a standard deviation of 4% of the ultimate load in direct tension. These tests included bolts from Lots 1, 2, 3, 4, 5, 10, 11 and 12. Lots 6, 7 and 8 were also tested in torqued tension, but a malfunction of the load cell made the results unusable. Because of the limited number of bolts available in Lot 9, this lot was excluded from torqued tension tests. Lot 13 was the last lot scheduled to be tested in this part of the program. After examination of the data from the other lots, it was felt that the results from these tests were not providing useful information. Consequently, it was decided to not include Lot 13 in the torqued tension testing.

A representative load vs. elongation plot for a bolt in torqued tension is given in Figure 4.1, along with the load vs. elongation plot for a bolt from the same lot loaded in direct tension. It can be seen that, up to the twist-off load (the load obtained when the splined end of a tension-control shears off during a normal tension-control bolt installation), the two responses are quite similar. This is expected, since, up to this point, the tension-control bolt would have been loaded entirely in direct tension. After twist-off, however, the torqued tension plot deviates significantly from the direct tension plot. This too is expected, since, after twist-off, any further tension placed in the bolt is obtained by turning the nut, which adds shear stresses to the shank of the bolt.

The reduction in ultimate load capacity for a regular high strength bolt loaded in torqued tension is been reported to be between 5% and 25% of the ultimate tensile load in direct tension, with an average of 15% (2). The bolts tested here showed a reduction of 12%. This implies that torqued tension loading on a tension-control bolt, as performed in this program, is really no different than torquing a regular A325 bolt to failure using an impact wrench.

Generally, it is expected that the ductility of a bolt pretensioned by turning the nut against the gripped material is less than that for the same bolt loaded in direct tension (2). As seen in Figure 4.1, this was not the case in these tests. The amount of ductility displayed in either mode is partly a reflection of the testing procedures and instrumentation used. However, another feature in the case of tension-control bolts is that the coefficient of friction between the nut and the bolt threads and between the nut and the clamped material is expected to be less than for an as-delivered standard A325 bolt. This should produce higher ultimate loads and ductility for the tension-control bolt in torqued tension. This was not demonstrated by the ultimate loads attained by the tension-control bolts in torqued tension and the validity of the ductility comparison between tension-control bolts loaded in direct tension and torqued tension is uncertain. The issue is mainly academic, however, since it is not expected that any field installation of a tension-control bolt would be taken past the point of twist-off of the splined end. Since the tension-control bolt system operates on the basis of torque control, reserve deformation capacity is not as beneficial here as it would be when using the turn-of-nut method for installation for a standard A325 bolt.

4.3 BOLT PRETENSIONS

4.3.1 Bolt Lot Conditions

The initial condition of the lots varied. Lot 1 was received in a sealed metal keg. Lot 2 was also received in a sealed metal keg, but the keg had been damaged during shipping. Although there was no rupture of the keg walls, there were a number of large dents around the bottom. Lots 3 and 4 were in plastic bags placed inside sealed kegs. Some of the bolts in these two lots were rusted—more so for Lot 3 than for Lot 4. Lot 5 was received in two cardboard boxes. The first box contained bolts only, while the second box contained additional bolts with some newspaper on top (presumably to keep the bolts from rattling around). These bolts were immediately transferred to a metal keg with a sealed lid. Lots 6 and 7 were received in sealed metal kegs. Lot 8 was received in a metal keg without a lid. This lot had been sitting in a fabricator's warehouse for some time without a lid and had accumulated sawdust. Upon receipt of this lot, a metal keg lid was supplied and the lid was sealed. Lot 9 was also received in a metal keg, but the lid was damaged and did not seal very well and the bolts in this lot appeared to have very little lubricant. The lid for this lot was refitted. Lot 10 arrived in plastic bags inside two cardboard boxes and was transferred to a metal keg upon receipt. Lots 11, 12 and 13 were also in cardboard boxes, but without plastic bags. Again, they were placed in metal kegs once they were received.

4.3.2 Presentation of Data

Herein, when normalized pretensions are given they will have been normalized with respect to the specified minimum pretension, unless otherwise noted. The value of the specified minimum pretension is 125 kN for a 3/4 in. diameter ASTM A325 bolt and 174 kN for a 7/8 in. diameter ASTM A325 bolt. This type of normalization gives an explicit description of the bolt performance and allows the pretension of bolts with different diameters to be grouped. In a broad sense, any normalized value of pretension above 1.00 is acceptable since the result shows that the specified minimum pretension has been exceeded. Of course, a pretension of exactly 1.00 may not be very desirable, as will be discussed later.

In some cases it is useful to normalize a bolt pretension with respect to the ultimate tensile strength of the lot from which the bolt came. This type of number is essentially an efficiency factor for the friction conditions on the bolt (lubricant, rust, thread damage, and contamination) and calibration of the bolt (the annular groove diameter). Theoretically, in the best case a bolt pretension would reach a value of 1.00 with respect to the tensile strength of its parent lot. This is unrealistic, however, and as will be seen later, most bolts reach a pretension that is about 70% of its ultimate tensile strength.

4.3.3 Thread Damage, Lubrication, and Contamination Tests

It is instructive to consider first the tests involving the thread damage and varying lubrication conditions. These tests provide illustrative information regarding the effects of thread and washer friction conditions. In the paragraphs that follow, as-delivered pretensions are often cited. These have not been discussed yet, but they will be discussed in the Section 4.3.5.

The results for the thread damage tests (performed on Lot 2) are given in Table 4.5. In the as-delivered condition, Lot 2 had a normalized pretension of 1.17, standard deviation 0.05, both with respect to the specified minimum pretension. After subjecting the bolts to intentional thread damage, the pretension ratio dropped to 1.12 with a standard deviation of 0.07. This would suggest that the so-called "normal handling" of a keg of bolts, as defined in this program, caused a reduction in pretension of 4.5%.

Although the sample size was small, it appears that the type of incidental thread damage imposed on these bolts does not reduce the installed bolt tension in a significant way. From examination of typical bolts in this program it seems that when the nuts, washers and bolts are shipped as an assembly there is little thread damage during transportation and handling.

Results from the thread lubrication study are provided in Table 4.6. When tested as-delivered, Lot 1 gave a normalized pretension of 1.31, standard deviation 0.09. After using mineral spirits to remove the lubricant from another sample of bolts from Lot 1, the pretension ratio dropped dramatically, to 0.81, standard deviation 0.07. Re-lubricating the threads and washers of bolts in this dry condition with lithium-based grease increased the pretension ratio to only 1.14, standard deviation 0.05, while re-lubricating with thread compound allowed the pretension ratio to rise, sharply, to 1.52, standard deviation 0.09. Re-lubricating the washers of dry bolts with lithium grease (but with the threads remaining in a dry condition) produced a pretension ratio of 1.07, standard deviation 0.08. Performing the same type of re-lubricating with thread compound instead of lithium grease provided a pretension ratio of 1.33, standard deviation 0.09.

In each of these tests, the standard deviation has remained relatively constant, at a value of about 0.08. Therefore, the averages can be compared directly in order to established the effects of the varying conditions. The normalized pretension of 0.81 achieved when the bolts had all the lubricant removed would clearly be unacceptable. It may not represent the worst case, however, since a lack of lubricant could be compounded by the presence of rust, thread damage, and contamination.

The test results for the case in which the threads and washers were re-lubricated with lithium grease are contrary to what was expected. It was anticipated that the pretension would return to a value close to the as-delivered pretension (1.31), but it only reached a value of 1.14. Using thread compound on the bolt threads and washers was effective. This thread compound is quite durable and is commonly applied to the threads of oil field drill pipe. In that situation it helps provide a seal at the pipe joint and keeps the pipe threads from deteriorating under the repeated threading and unthreading that occurs. The pretension attained when thread compound was used was 1.52, which corresponds to 87% of the ultimate tensile strength of Lot 1. The as-delivered pretension of 1.31 for this lot corresponds to 75% of the ultimate strength.

The tests in which the threads and washers were first cleaned with mineral spirits and then only the washers re-lubricated provides important information about the distribution of frictional torque between the threads and the washer. In the case where only the washer was re-lubricated with lithium grease, the pretension is only 6.5% less than when both the threads and the washer are re-lubricated. Thread compound on the washer only provided a pretension that was 14.3% less than the pretension achieved when both the threads and the washers were re-lubricated. These results suggest that about 86% and 94% of the frictional torque is coming from the nut–washer interface in these two cases. The trend was expected because the friction forces at the nut washer interface are at a greater radius with respect to the center of the bolt than are the friction forces on the threads, thereby producing a higher frictional torque for a constant coefficient of friction. Typically, only the nut of a bolt assembly is lubricated during the manufacturing. With time, this lubricant appears to spread somewhat to other parts of the bolt. However, with Lot 1 it appeared that the entire bolt assembly had been lubricated. Every part of the bolt, nut and washer was coated with lubricant, in contrast with the bolts of other suppliers. In addition, the lubricant provided on Lot 1 was more like a grease and seemed to be heavier than lubricant provided on the bolts of other suppliers. The normalized pretension provided by Lot 1, as-delivered, was 1.31, which is significantly above the overall average of 1.20 for all lots in the as-delivered condition. The ultimate tensile strength of Lot 1 was 218.4 kN, which is quite close to the overall average of 215.7 kN for all the 3/4 in. diameter lots. Since the normalized pretension for Lot 1 is 9.2% above the overall average, but the ultimate tensile strength of Lot 1 is only 1.3% greater than the overall average, this suggests that the friction conditions of Lot 1 were more favorable than for the average lot. These more favorable friction conditions are likely due to both lubricant quality and lubricant quantity.

Another sample of bolts, again from Lot 1 and in the as-delivered condition, was dropped into sandy soil, shown in Figure 4.2. As shown in Table 4.6, the normalized pretension for these bolts decreased to 1.17. The same type of test was performed again, but this time the bolts were dropped into the soil mixture without the nut and washer present. The normalized pretension for this condition was 1.27. The bolts used for this test are shown in Figure 4.3. It was expected that dropping the bolts into the soil without the nut or washer would result in lower pretensions, since the bolt threads would have more opportunity to take on soil particles. This did not occur, however. One explanation for this may be that the washer remained in good condition. As discussed above, the lubrication tests show that most of the frictional resistance comes from the nut–washer-joint interface. Therefore, since the washer and nut contact face were not contaminated by sandy soil, the pretension was higher.

4.3.4 Bolt Exposure Tests—Introduction

Tables 4.7 through 4.15 summarize the bolt pretensions measured for the 13 lots of bolts tested under the various conditions of exposure that have been described in Section 3.4.1. For each of the individual lots, these tables list the number of bolts tested, the average and standard deviation of the pretension (kN), the ratio of measured pretension to the specified minimum pretension, and the ratio of measured pretension to the ultimate tensile strength of each lot in direct tension. Finally, Tables 4.16 and 4.17 summarize the overall results.

When comparing the pretensions in any category of exposure, it must be kept in mind that the age of the bolts (i.e., age after lubrication) upon receipt for these tests was not constant. Ideally, each lot of bolts would have been lubricated and then shipped to the laboratory immediately, except for those cases where it was the deliberate intention to test bolts that had been stored by a supplier for extended periods. It was the intention that such a common baseline be established for these tests, but it was not possible to attain this goal within the time frame available. Thus, the "new" bolts actually varied in age after lubrication from about two weeks to 5-1/2 months. The disadvantage is obvious: comparison between lots is difficult, particularly when dealing with short storage periods. On the other hand, if the program had insisted upon newly-lubricated bolts, there was a risk that bolts would have been specially prepared for this program, thereby losing the advantage that these were all production lot bolts and presumably represent the types of bolts that could be expected by a consumer.

4.3.5 Bolts Stored Indoors in a Sealed Keg

Examination of the pretension results for the case where bolts were stored inside in a sealed keg show that there is very little change in the bolt pretension within the storage time periods used here. Including all the lots, the average as-delivered normalized pretension was 1.20, standard deviation 0.11. (The individual information for each lot is given in Table 4.7 and the summary information that combines all lots is provided in Table 4.16). A frequency plot for these bolts is given in Figure 4.4. (In this plot, and in all similar plots, a normal distribution curve for the data is also shown.) After two weeks of storage, the normalized pretension dropped to 1.16, standard deviation 0.17. When the bolts were tested at four weeks, however, the pretension ratio was 1.20, standard deviation 0.12. The frequency plot for these tests are provided in Figure 4.5 (two-week test) and Figure 4.6 (four-week test). As already stated, these comparisons are made on the basis of the average values obtained using all lots of bolts. Using these values, it appears that storage of the bolts in sealed kegs over a four week period did not degrade the lubricant on the bolts, thereby affecting the friction coefficient and reducing the pretension. Histograms for the as-delivered, two-week storage, and four-week storage tests are given in Figures 4.5, 4.6, and 4.7, respectively. Results for the individual lots are given in Tables 4.7, 4.8, and 4.9 for the as-delivered, two-week storage, and four-week storage.

A comparison of the pretensions can be made lot-by-lot, of course. This information is summarized in Table 4.17. For some lots there was little or no deterioration with time for these bolts stored indoors in a sealed keg (Lots 1, 5, 9, 11). These lots included bolts that were relatively old upon receipt (Lots 1 and 9) and relatively new (Lots 5 and 11). In other cases, there was a distinct drop at the two week mark (Lots 2 and 3), and the four week result was greater than the two-week values. However, there were some lots (Lots 10 and 13) where the two-week results were greater than either the as-delivered or four-week tests. (The lots not included in any of the listings above fall into intermediate cases.) Overall, it seems reasonable to conclude that there is no significant deterioration of installed pretensions when bolts are properly stored up to four weeks. This conclusion reflects tests on both bolts that were relatively new and bolts that were relatively old at the start of the controlled storage period.

In general, bolts from all the lots appeared to be in good condition upon receipt. A representative sample from a typical lot is shown in Figure 4.7. Thread lubricant is present, and there was no visible rust. However, as already noted, Lots 3 and 4 were received with some rust on the threads of some of the bolts. During the two and four weeks that the bolts were stored in the laboratory, there did not appear to be any further deterioration in the form of rust, although examination of the lubrication index (described, along with the rust, thread damage, and friction indices, in Section 3.4.1) shows that the lubricant, on average, decreased steadily from the as-delivered tests through to the four week tests. In the as-delivered state, the average lubrication index was 1.67. (This includes Lots 1 to 5 and Lots 10 to 13: they were the only lots for which the indices were noted). After two and four weeks, the index dropped to 1.34 and 1.25, respectively. The overall friction index for these three cases was 0.75, 1.19, and 0.92, respectively. The reason for the change in the friction index for both the two and four-week tests over the as-delivered tests was that the rust and damage indices for the as-delivered tests were higher than for both the two and four-week tests. This, of course, resulted in a lower friction index for the as-delivered tests. These results are provided in Table 4.18 for the various bolt exposure tests. The indices do not seem to support the trend of the measured pretensions results in this case.

4.3.6 Long-Term Indoor Storage

Additional tests were performed on Lots 1, 10 and, 11 after long term aging. The long term test for Lot 1 was done after approximately 32 weeks of storage while Lots 10, and 11 were tested after approximately 24 weeks of storage. After these storage periods, the ages of the specimens were approximately 132 weeks for Lot 1, 46 weeks for Lot 10 and 34 weeks for Lot 11. (These ages are measured from the time at which the bolts were lubricated.) The storage conditions for Lots 1 and 11 were identical to those previously described for the indoor storage condition—that is, inside a metal keg in the laboratory with the lid sealed shut. Lot 10 was stored in a similar fashion, but the lid was only loosely attached so that the bolts were well exposed to the air in the laboratory, which tends to be quite dry and dusty. The humidity in the laboratory generally ranges between 20% and 30%.

Lot 1 showed no appreciable change in pretension over this extended test period. The as-delivered, two week indoor storage, and four week indoor storage tests for Lot 1 provided normalized pretensions of 1.31, 1.34, and 1.32, with standard deviations of 0.09, 0.10, and 0.13, respectively. After the long term storage of Lot 1, the normalized pretension was 1.32, standard deviation 0.08. These bolts were already over two years old when they were received, so it is not surprising that there was no decrease in performance after the 32 weeks additional storage.

Bolts from Lot 11 provided normalized pretensions of 1.16, 1.13, and 1.14, and had standard deviations of 0.07, 0.13, and 0.07, for the as-delivered, two week indoor storage, and four week indoor storage, respectively. The normalized pretension after long term storage showed a small decrease, to 1.07, standard deviation 0.06. This suggests that after long periods of storage the bolt lubricant in these cases had a tendency to deteriorate, although more tests are needed in order to establish this definitively. Bolt Lot 11 was 5 months old upon receipt at the laboratory.

Bolts from Lot 10 gave normalized pretensions of 1.27, 1.34, and 1.31 in the as-delivered, two week, and four week indoor storage tests, respectively, with standard deviations of

0.05, 0.11, and 0.06, respectively. After 32 weeks, the pretension dropped to 1.21 and had a standard deviation of 0.05. This case is perhaps a more convincing example of the tendency for the lubricant to deteriorate with time since it would be reasonable to expect lubricant deterioration when bolts are given direct exposure to the air as occurred here. Furthermore, bolt lot 10 was only 2-1/2 months old upon receipt.

4.3.7 Bolts Exposed to Humidity

Allowing the bolts to be exposed to humidity in most cases resulted in lower pretensions upon installation. After two weeks, the normalized pretension of all lots tested was 1.16, standard deviation 0.14 (Table 4.16). At the four week mark, the normalized pretension of all lots tested was 1.17, standard deviation 0.13. The frequency plots for the two and four-week tests are given in Figures 4.8 and 4.9, respectively. Comparing these results with the as-delivered and indoor storage tests, it appears that the humidity had a mild effect on the bolts, that is, the bolt pretensions have decreased slightly. The average relative humidity and temperature for the two-week tests were 63.3% and 9.8°C, while the corresponding numbers for the four-week tests are 61.3% and 12.2°C. Tables 4.10 and 4.11 give the pretensions of individual lots for the two time intervals.

Comparison of the change in pretension between two and four weeks of exposure for the individual lots (provided in Table 4.17) shows that most lots experienced little or no deterioration between the two time periods (Lots 1, 3, 5, 9, 10, 11, 13). This is also seen in the overall average for all of the bolts tested in this series (Table 4.16). It might be reasonable to expect that pretensions would decrease further with longer exposures. However, the extent of the decrease should not be extrapolated from the two-week and four-week tests. Lots 2 and 12 showed a more substantial drop from the two-week tests to the four-week test. Lot 4 exhibited a small increase in pretension from the two to the four-week test.

The amount of lubrication on these bolts appeared to be comparable to the condition of the bolts in the two and four week tests on the bolts where storage was indoors in a sealed keg. The average lubrication indices for bolts exposed to humidity were 1.35 and 1.39 for the two and four week tests, respectively. The corresponding values for the two and four week tests on the bolts that were stored indoors in a sealed keg were 1.34 and 1.39, respectively.

Comparing lubrication indices between tests may be misleading, however. The lubrication index is simply a visual estimate of how "moist" the bolt threads appear. This moist appearance can result from either water condensation or bolt lubricant. Trying to distinguish between lubricant and water on the bolt threads would be difficult and the lubrication index would become even more subjective. Because of this, it is conceivable that a bolt may have a lubrication index of 3 (the maximum) without having any actual bolt lubricant, but a substantial amount of water condensation. However, it is reasonable to expect that if the condensation has degraded the lubricant to a great extent, more rust should appear on the bolt threads since the moisture would have a better exposure to the bolt steel.

The rust index was higher for the bolts that were exposed to humidity as compared with the as-delivered and indoor storage test bolts. At the two-week mark, the average rust index was 0.16, and it was 0.10 after four weeks of exposure. The bolts stored indoors had rust indices of 0.08 and 0.09 after two and four weeks, respectively. It should be noted that in the as-delivered condition the rust index was higher than either of these two exposures, with a value of 0.67. However, the lubrication index was also higher, at 1.67, which would be consistent with higher pretensions in the as-delivered condition as compared to the pretensions for bolts exposed to humidity. The average friction index for the two-week tests on bolts exposed to humidity was 1.07, while that for the four-week tests was 1.03.

The rust and thread damage indices are subjective measures, just as is the lubrication index. The examination for thread damage and rust was a global examination of the bolt threads; the overall appearance of the threads dictated the indices. The position of the rust or thread damage was not noted. The location of the rust or thread damage is significant, however, because of the way that bolt tensions are transferred to the nut. If the rust and thread damage are within the grip length or on the bolt threads that extend beyond the nut, there will be no effect on the bolt pretension. Most of the tension is taken by the nut threads that are closest to the clamped material, and the least amount of tension is taken by the nut threads on the bolt-end side of the nut. Thus, the most pronounced effect of rust and thread damage should occur when the rust and thread damage exist in the first few threads of the nut engagement.

The importance of the position of the lubricant follows a similar pattern: it would be desirable to have a lot of lubricant in the areas that transmit the most bolt tension (the first few threads on the nut). However, the lubricant tended to be more evenly distributed over the bolt threads than did the rust or threads damage.

For practical reasons, the position of the rust and thread damage were not recorded. Determining the position of damage or rust on the bolt would have taken a significant amount of time.

4.3.8 Bolts Given Full Exposure to the Weather

When the bolts were given full exposure to the weather, the pretension dropped further from that obtained when the bolts were exposed to humidity only. At two weeks the average normalized pretension registered 1.12, standard deviation 0.11 (Table 4.16). After four weeks, the pretension dropped to 1.10, standard deviation 0.11. Frequency diagrams for the two and four-week tests are provided in Figures 4.10 and 4.11, respectively. The pretensions here are lower than the pretensions from the tests on bolts exposed to humidity only, as expected. The average total precipitation, relative humidity, and temperature were 11.1 mm, 62.5%, and 9.8°C, for the two-week tests and 21.4 mm, 60.8%, and 12.2°C for the four week period. The pretensions for the individual lots are given in Tables 4.12 and 4.13.

Table 4.17 gives the results for this test series on a lot-by-lot basis. Most of the lots exhibited a decrease in pretension from the two-week to the four-week tests. Lots 1, 2, 4, and 13 showed a moderate decrease in pretension, while Lots 5, 10, and 12 showed a larger decrease. The pretension from Lot 9 decreased only slightly, and Lots 3 and 11 increased by a small amount. It appears, then, that in most cases the bolt pretensions decreased from the two-week to the four-week tests (in varying degrees), and that full exposure to the elements is more detrimental to the bolt pretensions than either the exposure to humidity or the indoor storage. This is as would be expected.

The friction index in this test series also dropped after four weeks, to a value of 0.08. The lubrication index declined from a value of 0.94 at two weeks to the four-week value of 0.75, as expected. Meanwhile, the rust index rose from a value of 0.43 at the two week mark to a value of 0.53 at the four week mark—again, this was expected. The decrease in the two and four-week test pretensions is in agreement with the decrease in the friction index. A typical group of bolts from the two-week test is shown in Figure 4.12, and bolts from the four-week test are shown in Figure 4.13. There is a small amount of rust on the bolts in Figure 4.12. Although the bolts in Figure 4.13 show additional rust, the amount of rust is not as much as might have been expected.

4.3.9 Bolts With Full Exposure to the Weather in a Simulated Joint

Bolts installed in the simulated joints after two weeks of full exposure to the weather showed a normalized pretension of 1.05, standard deviation of 0.10 (Table 4.16 and Figure 4.14). After four weeks, the pretension remained at 1.05, standard deviation 0.12 (Figure 4.15). After two weeks, the bolts tested had been exposed to an average total rainfall of 11.1 mm, during which time the average relative humidity and temperature were 62.5% and 9.7°C, respectively. Over the four weeks of exposure, there was 21.9 mm average total rainfall, with a relative humidity of 61.0% and temperature of 12.3°C. Pretensions for the individual lots are given in Tables 4.14 and 4.15 for the two time periods.

Table 4.17 shows that most lots experienced a moderate to large decrease in pretension between two weeks and four weeks exposure. The exceptions were Lots 4 and 12. Both of these lots showed a small increase in pretension. This is in contrast with the overall averages for all lots for the two and four-week tests. This discrepancy is explained below.

The four week test results for Lots 6, 7, and 8 are somewhat greater than the corresponding results for all other lots. However, two-week results were not obtained for lots 6, 7, and 8. The four-week test results for these lots are included in the average for all lots at the four week mark. If the four-week results for Lots 6, 7, and 8 are simply excluded from the four-week average because there is no two-week counterpart, the average normalized pretension for all lots at four weeks is 1.01, standard deviation 0.10. This is why the average pretension for all lots remains unchanged between the two and four week time periods whereas most of the lots show a decrease from the two to four-week tests. Regardless of how the data are manipulated, it seems clear that bolts installed snug-tight in a steel joint and then exposed to the weather for at least two weeks before final installation will suffer a significant decrease in attained pretension as compared with as-delivered bolts.

Although the measured pretensions in the weathered joint tests remained constant from two weeks to four weeks, the corresponding friction indices showed an increase, from 0.66 at two weeks to 0.83 at four weeks, mainly because the lubrication index was judged higher at four weeks than at two weeks (1.37 vs. 1.31). The most likely explanation for this apparent increase in lubricant is that these joints tended to harbor any water that seeped in. As previously mentioned, when the lubrication indices were judged, they were simply based on how "moist" the bolt threads looked, which may come from either lubricant or rain water. And, depending on the weather in and around the time of testing, the threads may or may not have been moistened. Regardless, the pretension is the main concern and it can be expected that the pretension will decrease with increased exposure.

Figures 4.16 and 4.17 show typical joints in which the bolts have been installed to the snug-tight condition. (The joints were stored in the orientation such that the longitudinal axis of the bolts was horizontal.) It was observed that a considerable amount of rusting had occurred at the sheared edges of the joint plates. Of course, conditions at the interior could not be observed. However, it was clear that the plates harbored rain water that had seeped in. The rusting of the plates and the containment of the rain water within the plates are the two main characteristics of the weathered joints that distinguishes them from the case wherein the bolts only were given full exposure.

Although the plates have rusted significantly, the part of the bolts extending beyond the nut have not. In Figure 4.18, two bolts have been removed from the joint and they are shown lying in front of the joint. The threads of these bolts have accumulated some rust, and, since the part of the bolts extending beyond the nut did not appear to have any rust, the rusting of the plates may have contributed to the rust found on the bolt threads contained within the grip length.

4.3.10 Statistical Variations in Measured Pretensions for the Various Exposures

The standard deviations for all the exposures considered in this program are generally similar. Typically, the normalized standard deviation was around 0.11 or 0.12. The largest standard deviation was 0.17 and coincided with the tests on the bolts that were stored indoors in a sealed keg for two weeks. The smallest deviation was 0.10 and occurred for the bolts that were weathered in a joint for two weeks and four weeks. The standard deviations are provided with the pretensions in the tables (Tables 4.7 to 4.17).

The *student's t-test* was applied to the pretension results for the various exposures and the tests involving different conditions of bolt lubrication. This test provides a measure of difference between the mean values of the samples with consideration given to the standard deviations and sizes of the samples. The *t* values calculated for the lots and their implications are provided in the following paragraphs. In the case of the lots subject to various exposures, the comparison is between the overall bolt pretension for the exposure in question and that for the as-delivered condition. In the case of the lots subject to various thread conditions, the comparison is between the pretension for the bolts with the thread condition in question and their as-delivered parent lot. Finally, when comparing the bolts that were re-lubricated on the washer only vs. re-lubricating the entire bolt assembly, the comparison is specifically between these two types of re-lubrication. When two distributions (e.g., as-delivered and weathered joint distributions) provide a *t* value that is "statistically significant" or "statistically different", this means that the two distributions provide different average bolt pretensions and should be differentiated.

Bolts that were stored indoors for two and four weeks have *t* values of 1.771 and 0.000, respectively, as compared to the average as-delivered pretension of all lots combined. Neither of these values is statistically significant at a 5% confidence level. In other words, these three lots of bolts seem to provide similar pretensions. The bolts that were exposed to humidity for two and four weeks provide *t* values of 2.012 and 1.667, respectively, as compared to the average as-delivered pretension of all lots. The two-week test is significantly different from the as-delivered pretension at the 5% confidence level while the four-week test is not. This means that the as-delivered and four-week tests provide similar pretensions, while the two-week test should be distinguished from the other two. The bolts that were given full exposure to the weather for two and four weeks give *t* values of 4.554 and 6.417, respectively, compared to the average as-delivered pretension of all lots. Both of these *t* values are significant at the 0.1% confidence level. Weathering bolts in a simulated steel joint for two and four weeks provide *t* values of 9.420 and 9.039, respectively, compared to the average as-delivered pretension of all lots. These *t* values are also significant at the 0.1% confidence level.

The lot of bolts that had its lubricant completely removed from the entire bolt assembly has a *t* value of 13.868 when compared with the as-delivered pretension of the parent lot (Lot 1). This is significant at the 0.1% level. The bolts that were re-lubricated with lithium grease on the entire bolt assembly give a *t* value, compared to the as-delivered pretension of the parent lot, of 5.222 which is significant at the 0.1% confidence level. Re-lubricating with thread compound gives a *t* value of 5.217, compared to the parent lot in the as-delivered condition, and this is also significant at the 0.1% level. Contaminating the bolts with sandy soil while the nut and washer were on the bolt and contaminating the bolt threads only (nut and washer not contaminated) provide *t* values of 3.677 and 0.994, compared to the as-delivered pretension of the parent lot. The first *t* value is significant at the 1% level while the second is not significant at the 5% level. Subjecting bolts to intentional thread damage gives a *t* value of 1.744, which is not significant at the 5% level.

The final comparisons required are between the bolts that were fully re-lubricated with either lithium grease or thread compound on the threads and washers, and those that were re-lubricated with lithium grease or thread compound on the washer only. In the case of lithium grease re-lubrication, the data for full re-lubrication and re-lubricating on the washer only gives a *t* value of 2.346. This is significant at the 5% level. Re-lubricating with thread compound gives a t value of 4.721, which is significant at the 0.1% level.

4.3.11 Variation of Bolt Pretension Among Suppliers

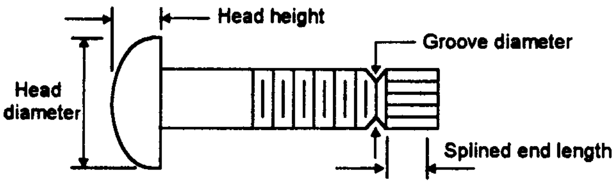
Three lots of bolts (Lots 3, 4, 5) were acquired from Supplier B, five lots (Lots 1, 6, 7, 8, 9) came from Supplier C and single lots came from Suppliers A, D, E, and F. (See Table 3.1.) The pretension results for the lots provided by Suppliers B and C are restated in Table 4.19. Examination of this table provides information on the variation in pretensions for bolts produced by a supplier.

The three lots of bolts from Supplier B produced only moderate variations in pretension within a given category of exposure. The largest difference is in the as-delivered condition, where the range of normalized pretensions for these lots ranged from 1.21 to 1.37. The measured pretensions for the three lots after two and four weeks of indoor storage show the normalized pretensions are generally around 1.20 to 1.24. This amount of variation is typical for about half of the tests on the three lots—that is, a difference in normalized pretension between the lots of only 0.04. This occurs for the two-week indoor storage, the two-week and four-week humidity exposures, and the two-week steel joint weathering test. The four-week indoor storage and the two-week and four-week full exposures have normalized pretension differences of about 0.08. The four-week exposure in a steel joint falls in-between with a difference of 0.06. Lot 3 has the highest pretension in four of the nine exposure cases, while Lot 4 has the highest pretension in three cases and Lot 5 has the highest pretension in two cases. Conversely, Lot 3 has the lowest pretension in two exposure categories, Lot 4 has the lowest pretension in four of the categories, and Lot 5 has the lowest pretension in three categories.

The five lots from Supplier C exhibited higher variations in pretension than did Supplier B. In the as-delivered condition, Lot 1 had a normalized pretension of 1.31, while Lot 9 had a normalized pretension of only 1.05. Similar differences between these two lots also exist in the two and four-week indoor storage tests. As seen in Table 4.19, as the type of exposure becomes more and more detrimental to the bolts (approaching the weathered joint tests), the difference between Lot 1 and Lot 9 shrinks. However, the smallest difference between the two lots is 0.20, which is still large. It should be recalled that Lot 9 was received with the thread lubrication judged to be poor (Section 4.3.1). Although there was no rust on the bolts and there did not appear to be excessive thread damage, there was very little lubricant. This was likely due to the storage conditions of the bolts before being submitted to the test program. While in the fabricator's warehouse, the lid on the keg did not seal and the bolts were probably quite old, although the production date is not known. In addition, Lot 9, unlike the other lots, consisted of 7/8 in. diameter bolts, which may or may not have been a factor in the performance of the lot. Bolt diameter *per se* probably should not have an effect on installed pretension, but comparative tests should be performed before reaching any conclusions.

Excluding Lot 9 and comparing Lots 1, 6, 7, and 8 (all from Supplier C), the variation in pretension is much less pronounced. However, the variations are either comparable to or larger than the differences found in the lots from Supplier B. In the four-week tests for bolts stored indoors and bolts exposed to humidity, the maximum difference in normalized pretensions is about 0.12. The four-week test on bolts with full exposure and bolts weathered in a steel joint show a maximum normalized pretension difference of 0.07, which is similar to the larger variations seen in the bolts from Supplier B. In summary, there appears to be a significant variation in the pretensions of bolts received from Supplier C.

Table 4.1
Bolt Dimensions



Bolt Lot	*Head Diameter (in.)*		*Head Height (in.)*		*Groove Diameter (in.)*		*Splined End Length(in.)*	
	Average	*Standard Deviation*	*Average*	*Standard Deviation*	*Average*	*Standard Deviation*	*Average*	*Standard Deviation*
1	1.391	0.015	0.470	0.018	0.532	0.002	0.646	0.021
2	1.221†	0.002†	0.476	0.001	0.528	0.001	0.572	0.019
5	1.564	0.016	0.492	0.004	0.530	0.001	0.645	0.002
10	1.431	0.009	0.471	0.009	0.528	0.001	0.612	0.014
11	1.585	0.005	0.475	0.003	0.529	0.001	0.584	0.009
12	1.520	0.015	0.472	0.012	0.530	0.001	0.621	0.007
13	1.348	0.019	0.488	0.003	0.535	0.001	0.612	0.003
All Lots‡	1.473	0.092	0.478	0.012	0.530	0.003	0.613	0.028

† Since Lot 2 had a regular hex head, head diameter refers to the length across the head flats.

‡ Excluding Lot 2 (regular hex head).

Table 4.2
Measured Ultimate Tensile Strength/Specified Ultimate Tensile Strength

Bolt Lot	*No. Tested*	*Average Measured Ult. Tensile Strength / Specified Ult. Tensile Strength*	*Std. Dev. Measured Ult. Tensile Strength / Specified Ult. Tensile Strength*
1	5	1.23	0.033
2	5	1.06	0.004
3	5	1.31	0.008
4	5	1.31	0.021
5	5	1.26	0.022
6	5	1.23	0.013
7	5	1.18	0.008
8	5	1.22	0.009
9	4	1.20	0.027
10	5	1.27	0.013
11	5	1.20	0.018
12	5	1.12	0.010
13	5	1.15	0.002
All Lots	64	1.21	0.070

Table 4.3

Rockwell C Hardness

Bolt Lot	*No. Tested*	*Average Rockwell C Hardness*	*Standard Deviation of the Hardness*
1	5	30.5	2.15
2	5	29.9	0.84
3	5	32.2	2.10
4	5	31.5	2.13
5	5	25.4	6.11
6	5	31.1	1.89
7	5	27.9	1.31
8	5	28.9	2.58
9	4	28.0	1.24
10	5	31.2	3.06
11	5	28.9	1.48
12	5	28.0	1.27
13	5	28.3	0.96
All Lots	64	29.4	3.16

Table 4.4
Average Measured Ultimate Tensile Load in Torqued Tension

Bolt Lot	*No. Tested*	$\frac{\textit{Ave. Measured Ult. Tens. Strength Torqued}}{\textit{Ave. Ult. Tens. Strength Direct Tension}}$	$\frac{\textit{Std.Dev. Measured Ult. Tens. Strength Torqued}}{\textit{Ave. Ult. Tens. Strength Direct Tension}}$
1	5	0.93	0.05
2	5	0.92	0.03
3	4	0.84	0.03
4	4	0.86	0.06
5	5	0.89	0.01
10	5	0.87	0.03
11	5	0.86	0.04
12	5	0.86	0.03
All Lots	38	0.88	0.04

Table 4.5
Intentional Thread Damage Test Results

Item	*Lot 2 As-Delivered*	*Lot 2 with Thread Damage*
Number Tested	9	9
Pretension (kN)	146	141
Standard Deviation (kN)	5.9	9.3
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.17	1.12
Standard Deviation	0.05	0.07
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.77	0.74

Table 4.6
Lubrication Test Pretension Results (All bolts from Lot 1)

Item	*As-Delivered*	*No Lubricant on the Assembly*	*Re-Lubricated with Lithium Grease*		*Re-Lubricated with Thread Compound*		*Threads Contaminated*	
			Washer and Threads	*Washer Only*	*Washer and Threads*	*Washer Only*	*Nut and Washer on Bolt*	*Nut and Washer not on Bolt*
Number Tested	10	10	10	10	10	10	10	10
Pretension (kN)	164	101	143	134	190	167	146	159
Standard Deviation (kN)	11.6	9.0	6.5	9.8	10.8	10.7	10.0	11.1
$\frac{\text{Pretension}}{\text{Specified Minimum Pretension}}$	1.31	0.81	1.14	1.07	1.52	1.33	1.17	1.27
Standard Deviation	0.09	0.07	0.05	0.08	0.09	0.09	0.08	0.09
$\frac{\text{Pretension}}{\text{Ult. Tensile Str. in Direct Tension}}$	0.75	0.46	0.65	0.62	0.87	0.76	0.67	0.73

Table 4.7
Bolt Pretensions As-Delivered

Item	*Lot 1*	*Lot 2*	*Lot 3*	*Lot 4*	*Lot 5*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*	*Lot 10*	*Lot 11*	*Lot 12*	*Lot 13*
Number Tested	10	9	6	6	9	–	–	–	5	9	9	9	9
Pretension (kN)	164	146	171	153	151	–	–	–	182	158	145	141	140
Standard Deviation (kN)	11.6	5.9	13.9	14.2	5.2	–	–	–	6.5	6.6	9.1	7.7	3.7
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.31	1.17	1.37	1.23	1.21	–	–	–	1.05	1.27	1.16	1.13	1.12
Standard Deviation	0.09	0.05	0.11	0.11	0.04	–	–	–	0.04	0.05	0.07	0.06	0.03
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.75	0.77	0.74	0.66	0.67	–	–	–	0.61	0.70	0.68	0.70	0.69

Table 4.8
Bolt Pretensions for Bolts Stored Indoors in a Sealed Keg for Two Weeks

Item	*Lot 1*	*Lot 2*	*Lot 3*	*Lot 4*	*Lot 5*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*	*Lot 10*	*Lot 11*	*Lot 12*	*Lot 13*
Number Tested	9	8	6	6	9	–	–	–	5	9	9	9	9
Pretension (kN)	168	106	150	155	151	–	–	–	186	167	141	130	146
Standard Deviation (kN)	12.3	12.5	13.0	10.2	12.7	–	–	–	7.1	14.2	16.2	9.4	3.6
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.34	0.85	1.20	1.24	1.21	–	–	–	1.07	1.34	1.13	1.04	1.17
Standard Deviation	0.10	0.10	0.10	0.08	0.10	–	–	–	0.04	0.11	0.13	0.08	0.03
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.77	0.56	0.65	0.66	0.67	–	–	–	0.62	0.74	0.66	0.65	0.71

Table 4.9
Bolt Pretensions for Bolts Stored Indoors in a Sealed Keg for Four Weeks

Item	*Lot 1*	*Lot 2*	*Lot 3*	*Lot 4*	*Lot 5*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*	*Lot 10*	*Lot 11*	*Lot 12*	*Lot 13*
Number Tested	8	9	6	6	9	8	9	9	5	9	8	10	9
Pretension (kN)	165	142	155	162	151	157	149	155	177	163	143	137	142
Standard Deviation (kN)	16.1	15.2	5.1	14.6	12.4	12.0	12.3	9.4	13.3	7.3	8.7	6.4	5.1
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.32	1.13	1.24	1.30	1.21	1.26	1.19	1.24	1.02	1.31	1.14	1.09	1.14
Standard Deviation	0.13	0.12	0.04	0.12	0.10	0.10	0.10	0.08	0.08	0.06	0.07	0.05	0.04
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.76	0.75	0.67	0.70	0.68	0.72	0.71	0.72	0.59	0.72	0.67	0.68	0.70

Table 4.10

Bolt Pretensions for Bolts Exposed to Humidity for Two Weeks

Item	*Lot 1*	*Lot 2*	*Lot 3*	*Lot 4*	*Lot 5*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*	*Lot 10*	*Lot 11*	*Lot 12*	*Lot 13*
Number Tested	9	9	6	6	8	–	–	–	5	9	9	9	9
Pretension (kN)	172	134	150	142	145	–	–	–	180	164	132	134	146
Standard Deviation (kN)	8.7	17.0	9.3	21.7	9.5	–	–	–	3.3	16.3	5.9	9.5	5.2
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.37	1.08	1.20	1.14	1.16	–	–	–	1.03	1.31	1.06	1.07	1.17
Standard Deviation	0.07	0.14	0.07	0.17	0.08	–	–	–	0.02	0.13	0.05	0.08	0.04
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.79	0.71	0.64	0.61	0.65	–	–	–	0.60	0.72	0.62	0.67	0.72

Table 4.11

Bolt Pretensions for Bolts Exposed to Humidity for Four Weeks

Item	*Lot 1*	*Lot 2*	*Lot 3*	*Lot 4*	*Lot 5*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*	*Lot 10*	*Lot 11*	*Lot 12*	*Lot 13*
Number Tested	8	9	6	6	9	9	9	9	5	8	9	9	9
Pretension (kN)	170	127	148	145	143	155	156	161	179	162	133	128	144
Standard Deviation (kN)	15.6	16.6	8.6	6.3	7.6	4.2	9.2	8.6	12.4	4.8	11.0	12.2	3.9
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.36	1.02	1.19	1.16	1.15	1.24	1.24	1.29	1.03	1.29	1.06	1.03	1.15
Standard Deviation	0.13	0.13	0.07	0.05	0.06	0.03	0.07	0.07	0.07	0.04	0.09	0.10	0.03
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.78	0.67	0.64	0.62	0.64	0.71	0.74	0.74	0.60	0.72	0.62	0.64	0.70

Table 4.12
Bolt Pretensions for Bolts Fully Exposed to the Weather for Two Weeks

Item	*Lot 1*	*Lot 2*	*Lot 3*	*Lot 4*	*Lot 5*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*	*Lot 10*	*Lot 11*	*Lot 12*	*Lot 13*
Number Tested	9	6	6	6	9	-	-	-	5	9	9	8	9
Pretension (kN)	154	119	146	142	153	-	-	-	171	146	138	129	143
Standard Deviation (kN)	7.7	12.9	6.8	6.2	7.2	-	-	-	1.1	8.7	12.7	5.9	9.5
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.23	0.95	1.17	1.14	1.23	-	-	-	0.98	1.16	1.10	1.03	1.14
Standard Deviation	0.06	0.10	0.05	0.05	0.06	-	-	-	0.01	0.07	0.10	0.05	0.08
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.70	0.63	0.63	0.61	0.68	-	-	-	0.58	0.64	0.63	0.64	0.70

Table 4.13
Bolt Pretensions for Bolts Fully Exposed to the Weather for Four Weeks

Item	*Lot 1*	*Lot 2*	*Lot 3*	*Lot 4*	*Lot 5*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*	*Lot 10*	*Lot 11*	*Lot 12*	*Lot 13*
Number Tested	9	9	5	6	9	8	9	9	5	9	9	9	9
Pretension (kN)	149	123	147	137	144	150	146	141	169	136	139	119	138
Standard Deviation (kN)	10.2	9.0	14.3	10.3	4.8	6.7	8.3	8.5	4.5	14.7	8.8	11.3	3.3
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.19	0.98	1.18	1.10	1.15	1.20	1.17	1.13	0.97	1.09	1.11	0.95	1.11
Standard Deviation	0.08	0.07	0.11	0.08	0.04	0.05	0.07	0.07	0.03	0.12	0.07	0.09	0.03
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.68	0.65	0.63	0.59	0.64	0.69	0.70	0.65	0.56	0.60	0.65	0.59	0.68

Table 4.14
Bolt Pretensions for Bolts Fully Exposed to the Weather in a Simulated Steel Joint for Two Weeks

Item	*Lot 1*	*Lot 2*	*Lot 3*	*Lot 4*	*Lot 5*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*	*Lot 10*	*Lot 11*	*Lot 12*	*Lot 13*
Number Tested	10	10	10	10	10	-	-	-	8	10	10	6	9
Pretension (kN)	151	118	127	125	130	-	-	-	176	145	127	117	144
Standard Deviation (kN)	4.5	5.3	7.0	6.7	6.9	-	-	-	13.2	7.3	8.6	7.1	4.9
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.21	0.95	1.02	1.00	1.04	-	-	-	1.01	1.16	1.02	0.93	1.15
Standard Deviation	0.04	0.04	0.06	0.05	0.05	-	-	-	0.08	0.06	0.07	0.06	0.04
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.69	0.62	0.55	0.54	0.58	-	-	-	0.59	0.64	0.59	0.58	0.70

Table 4.15
Bolt Pretensions for Bolts Fully Exposed to the Weather in a Simulated Steel Joint for Four Weeks

Item	*Lot 1*	*Lot 2*	*Lot 3*	*Lot 4*	*Lot 5*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*	*Lot 10*	*Lot 11*	*Lot 12*	*Lot 13*
Number Tested	10	10	10	10	10	10	8	10	8	10	9	10	9
Pretension (kN)	145	113	123	130	124	149	145	153	167	136	118	118	134
Standard Deviation (kN)	5.4	6.4	9.1	6.4	11.3	6.0	10.6	11.0	7.3	10.0	4.1	4.7	10.7
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.16	0.90	0.98	1.04	0.99	1.19	1.16	1.23	0.96	1.09	0.95	0.95	1.07
Standard Deviation	0.04	0.05	0.07	0.05	0.09	0.05	0.08	0.09	0.04	0.08	0.03	0.04	0.09
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.66	0.59	0.53	0.56	0.55	0.68	0.69	0.71	0.56	0.60	0.55	0.59	0.65

Table 4.16
Bolt Pretensions for the Various Test Series

Item	*As–Delivered*	*Stored Indoors*		*Exposed to Humidity*		*Full Exposure to the Weather*		*Weathered in a Steel Joint*	
		2 Weeks	*4 Weeks*	*2 Weeks*	*4 Weeks*	*2 Weeks*	*4 Weeks*	*2 Weeks*	*4 Weeks*
Number Tested	81	79	105	79	105	76	105	93	124
Pretension (kN)‡	153	149	152	149	149	143	140	136	134
Standard Deviation (kN)‡	14.6	23.1	14.9	18.9	17.5	14.5	14.3	17.9	17.1
$\frac{\textit{Pretension}}{\textit{Specified Minimum Pretension}}$	1.20	1.16	1.20	1.16	1.17	1.12	1.10	1.05	1.05
Standard Deviation	0.11	0.17	0.12	0.14	0.13	0.11	0.11	0.10	0.12
$\frac{\textit{Pretension}}{\textit{Ult. Tensile Str. in Direct Tension}}$	0.70	0.67	0.70	0.68	0.68	0.65	0.64	0.61	0.61

‡ These values do not include Lot 9 since Lot 9 consisted of 7/8 in. diameter bolts, while the other lots were 3/4 in. diameter bolts.

Table 4.17
Bolt Pretensions for the Various Exposures

Lot	*As–Delivered*	*Stored Indoors*		*Exposed to Humidity*		*Full Exposure to the Weather*		*Weathered in a Steel Joint*	
		2 Weeks	*4 Weeks*	*2 Weeks*	*4 Weeks*	*2 Weeks*	*4 Weeks*	*2 Weeks*	*4 Weeks*
1	1.31 (0.09)	1.34 (0.10)	1.32 (0.13)	1.37 (0.07)	1.36 (0.13)	1.23 (0.06)	1.19 (0.08)	1.21 (0.04)	1.16 (0.04)
2	1.17 (0.05)	0.85 (0.10)	1.13 (0.12)	1.08 (0.14)	1.02 (0.13)	0.95 (0.10)	0.98 (0.07)	0.95 (0.04)	0.90 (0.05)
3	1.37 (0.11)	1.20 (0.10)	1.24 (0.04)	1.20 (0.07)	1.19 (0.07)	1.17 (0.05)	1.18 (0.11)	1.02 (0.06)	0.98 (0.07)
4	1.23 (0.11)	1.24 (0.08)	1.30 (0.12)	1.14 (0.17)	1.16 (0.05)	1.14 (0.05)	1.10 (0.08)	1.00 (0.05)	1.04 (0.05)
5	1.21 (0.04)	1.21 (0.10)	1.21 (0.10)	1.16 (0.08)	1.15 (0.06)	1.23 (0.06)	1.15 (0.04)	1.04 (0.05)	0.99 (0.09)
6	—	—	1.26 (0.10)	—	1.24 (0.03)	—	1.20 (0.05)	—	1.19 (0.05)
7	—	—	1.19 (0.10)	—	1.24 (0.07)	—	1.17 (0.07)	—	1.16 (0.08)
8	—	—	1.24 (0.08)	—	1.29 (0.07)	—	1.13 (0.07)	—	1.23 (0.09)
9	1.05 (0.04)	1.07 (0.04)	1.02 (0.08)	1.03 (0.02)	1.03 (0.07)	0.98 (0.01)	0.97 (0.03)	1.01 (0.08)	0.96 (0.04)
10	1.27 (0.05)	1.34 (0.11)	1.31 (0.06)	1.31 (0.13)	1.29 (0.04)	1.16 (0.07)	1.09 (0.12)	1.16 (0.06)	1.09 (0.08)
11	1.16 (0.07)	1.13 (0.13)	1.14 (0.07)	1.06 (0.05)	1.06 (0.09)	1.10 (0.10)	1.11 (0.07)	1.02 (0.07)	0.95 (0.03)
12	1.13 (0.06)	1.04 (0.08)	1.09 (0.05)	1.07 (0.08)	1.03 (0.10)	1.03 (0.05)	0.95 (0.09)	0.93 (0.06)	0.95 (0.04)
13	1.12 (0.03)	1.17 (0.03)	1.14 (0.04)	1.17 (0.04)	1.15 (0.03)	1.14 (0.08)	1.11 (0.03)	1.15 (0.04)	1.07 (0.09)

Note 3: Standard deviations are given in brackets. For the number of bolts in each category, see Tables 4.7 to 4.15.

Table 4.18
Average Friction Indices for the Various Bolt Exposure Series

Index	*As–Delivered*	*Stored Indoors*		*Exposed to Humidity*		*Full Exposure to the Weather*		*Weathered in a Steel Joint*	
		2 Weeks	*4 Weeks*	*2 Weeks*	*4 Weeks*	*2 Weeks*	*4 Weeks*	*2 Weeks*	*4 Weeks*
Average Lubricant Index	1.67	1.34	1.25	1.35	1.39	0.94	0.75	1.31	1.37
Average Rust Index	0.27	0.08	0.09	0.16	0.10	0.43	0.53	0.59	0.51
Average Thread Damage Index	0.57	0.07	0.20	0.07	0.24	0.17	0.05	0.06	0.03
Average Friction Index	0.75	1.19	0.92	1.07	1.03	0.29	0.08	0.66	0.83
Standard Deviation of the Friction Index	0.94	0.52	0.78	0.68	0.56	0.08	1.18	0.65	0.49

Table 4.19
Variation of Normalized Pretensions Among Suppliers

Test	*Supplier B*			*Supplier C*				
	Lot 3	*Lot 4*	*Lot 5*	*Lot 1*	*Lot 6*	*Lot 7*	*Lot 8*	*Lot 9*
Bolts As-Delivered	1.37	1.23	1.21	1.31	—	—	—	1.05
Bolts Stored Indoors for Two Weeks	1.20	1.24	1.21	1.34	—	—	—	1.07
Bolts Stored Indoors for Four Weeks	1.24	1.30	1.21	1.32	1.26	1.19	1.24	1.02
Bolts Exposed to Humidity for Two Weeks	1.20	1.14	1.16	1.37	—	—	—	1.03
Bolts Exposed to Humidity for Four Weeks	1.19	1.16	1.15	1.36	1.24	1.24	1.29	1.03
Bolts with Full Exposure to the Weather for Two Weeks	1.17	1.14	1.23	1.23	—	—	—	0.98
Bolts with Full Exposure to the Weather for Four Weeks	1.18	1.10	1.15	1.19	1.20	1.17	1.13	0.97
Bolts Weathered in a Steel Joint for Two Weeks	1.02	1.00	1.04	1.21	—	—	—	1.01
Bolts Weathered in a Steel Joint for Four Weeks	0.98	1.04	0.99	1.16	1.19	1.16	1.23	0.96

Note: For the number of bolts in each category, see Tables 4.7 to 4.15.

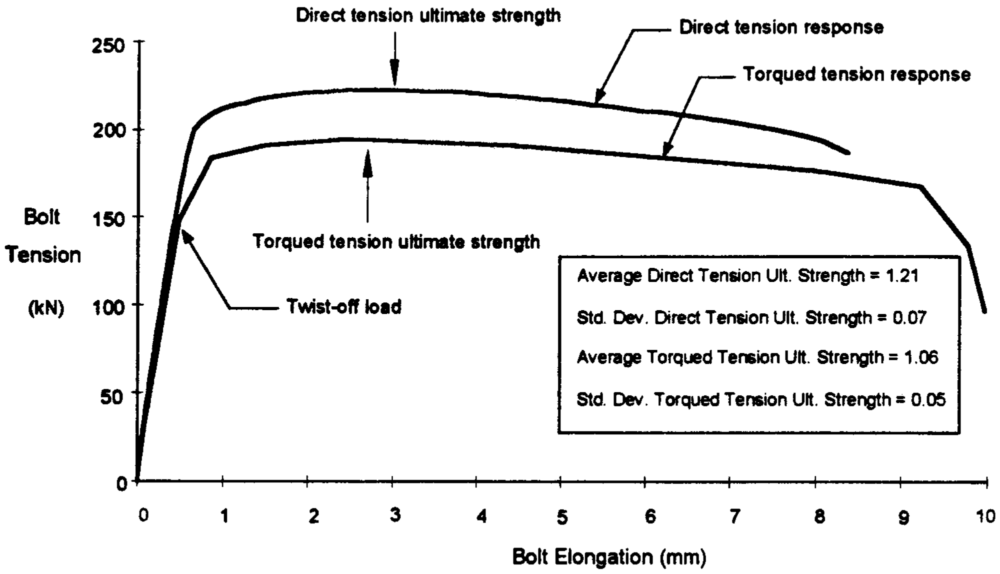


Fig. 4.1 Load vs. elongation for bolts loaded in torqued tension and direct tension

Fig. 4.2. Bolts dropped in sandy soil before being tested

Fig. 4.3. Bolts dropped in sandy soil without the nut or washer before being tested

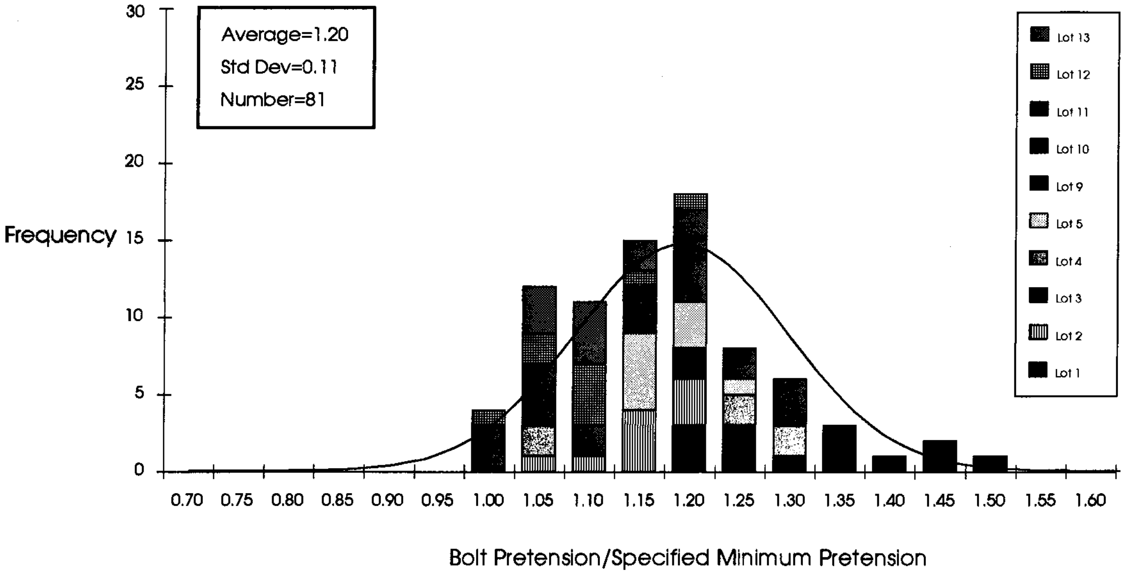


Fig. 4.4. Histogram of bolt pretensions in the as-delivered condition

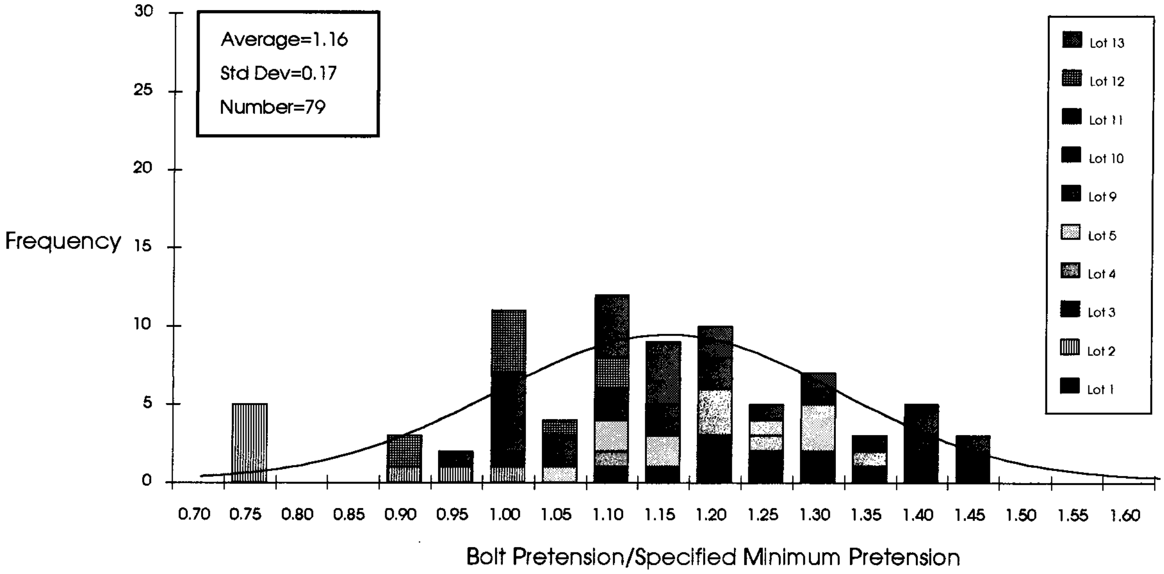


Fig. 4.5. Histogram of bolt pretensions for bolts stored indoors in a sealed keg for two weeks

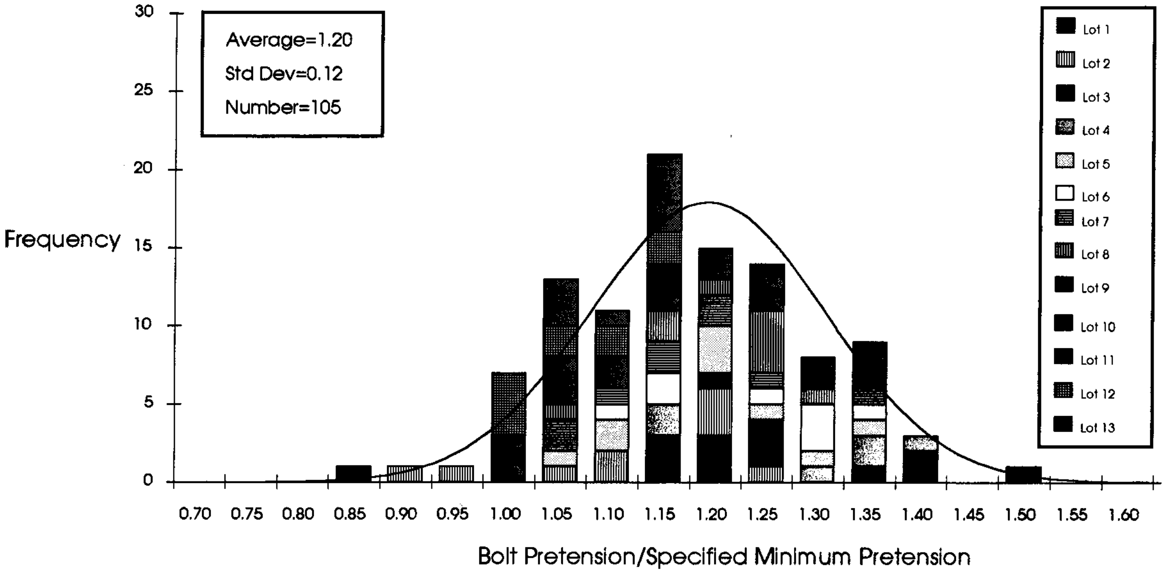


Fig. 4.6. Histogram of bolt pretensions for bolts stored indoors in a sealed keg for four weeks

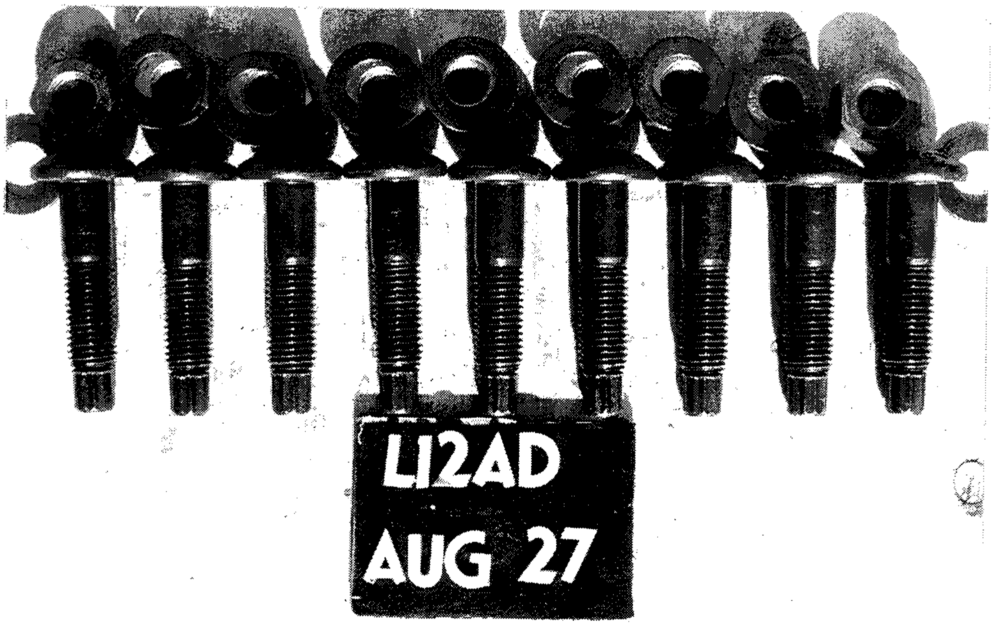


Fig. 4.7. Typical bolts as-delivered

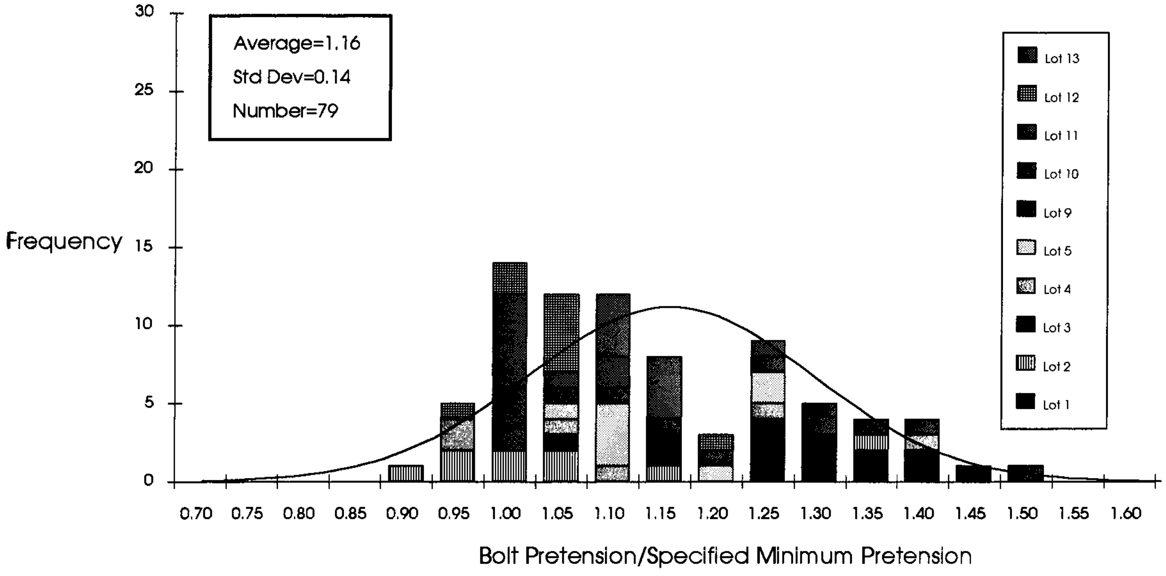


Fig. 4.8. Histogram of bolt pretensions for bolts exposed to humidity for two weeks

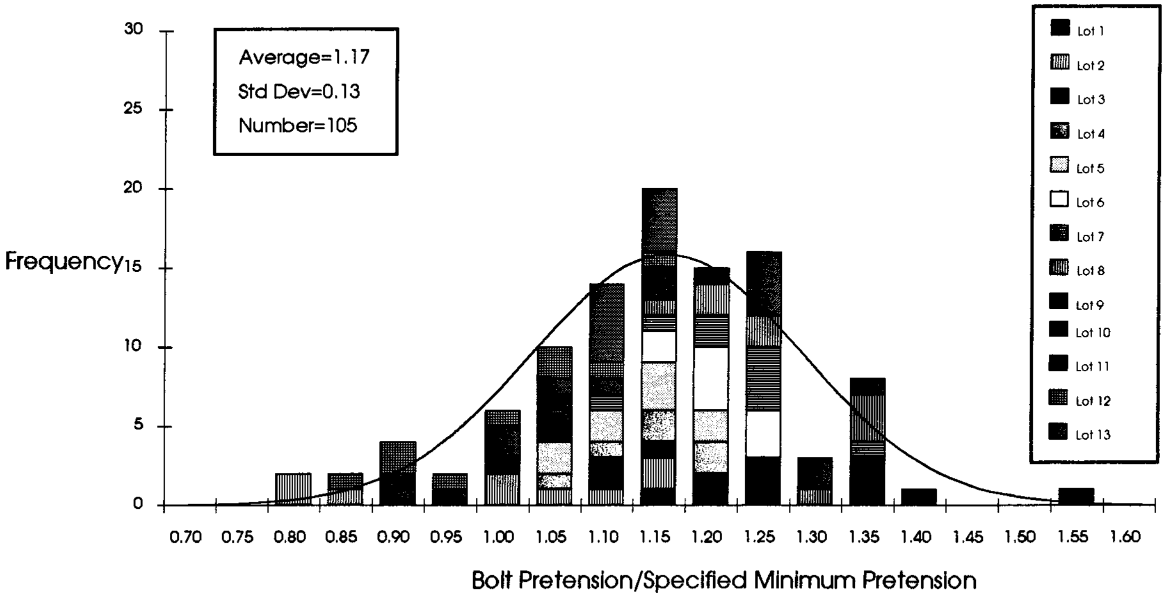


Fig. 4.9. Histogram of bolt pretensions for bolts exposed to humidity for four weeks

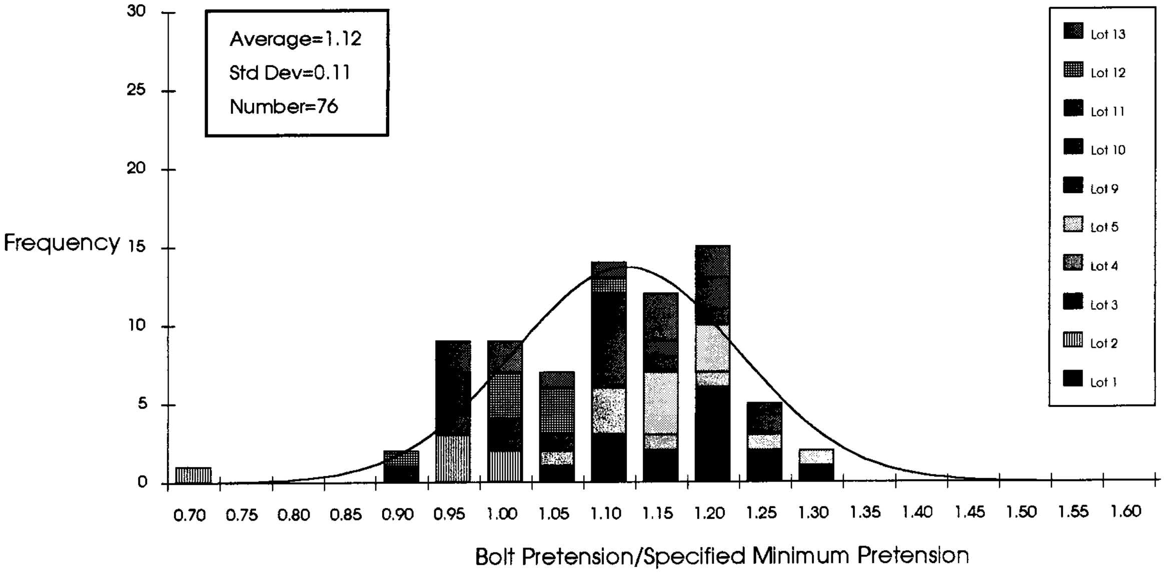


Fig. 4.10. Histogram of bolt pretensions for bolts given full exposure to the weather for two weeks

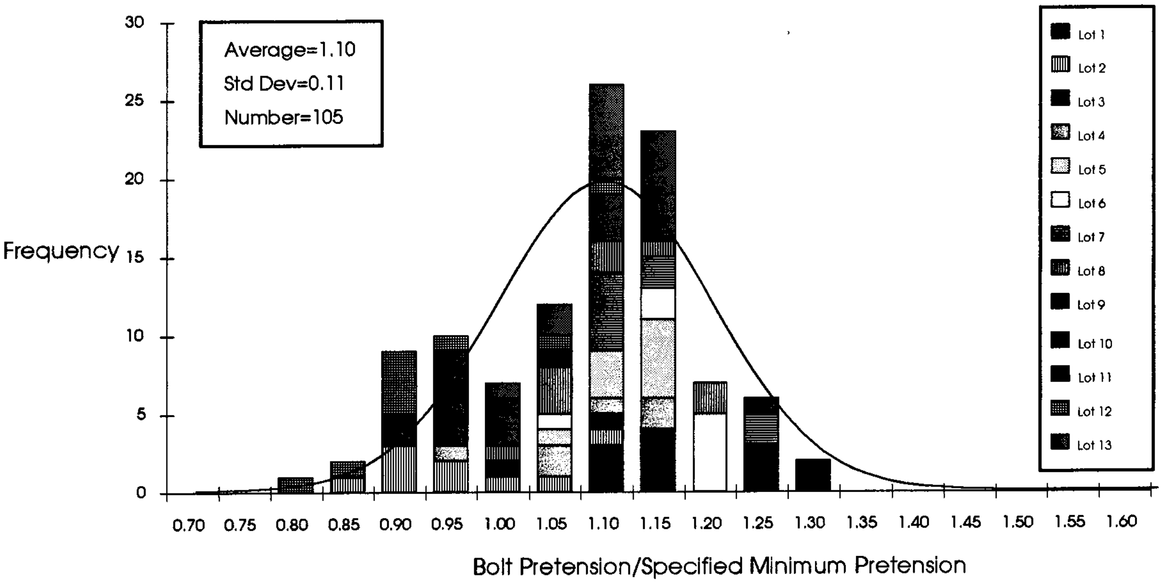


Fig. 4.11. Histogram of bolt pretensions for bolts given full exposure to the weather for four weeks

Fig. 4.12. Typical bolts after full exposure to the weather for two weeks

Fig. 4.13. Typical bolts after full exposure to the weather for four weeks

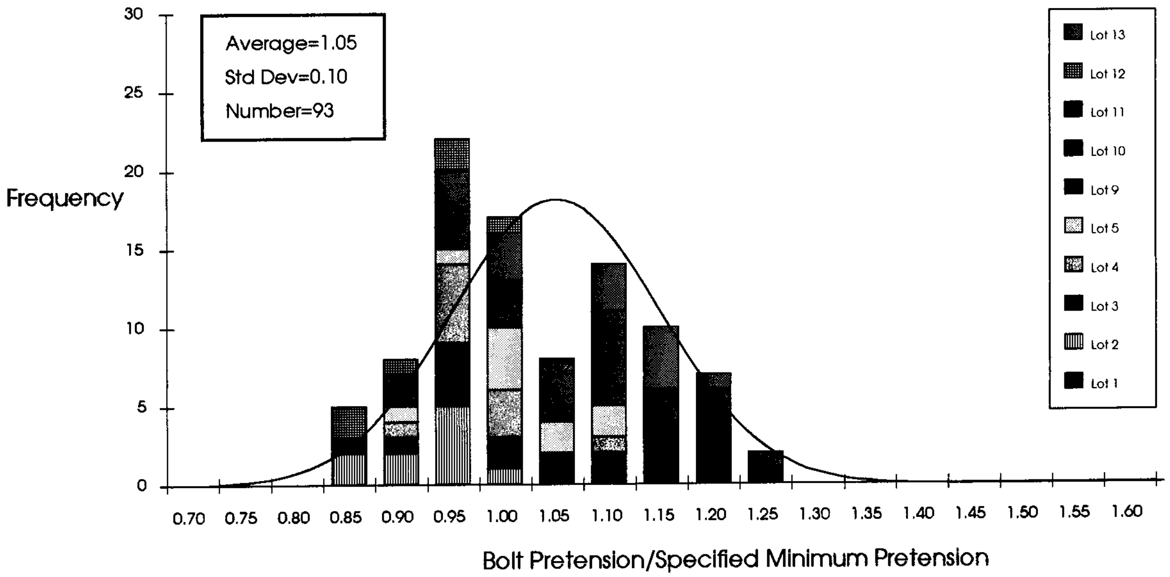


Fig. 4.14. Histogram of bolt pretensions for bolts weathered in a simulated steel joint for two weeks

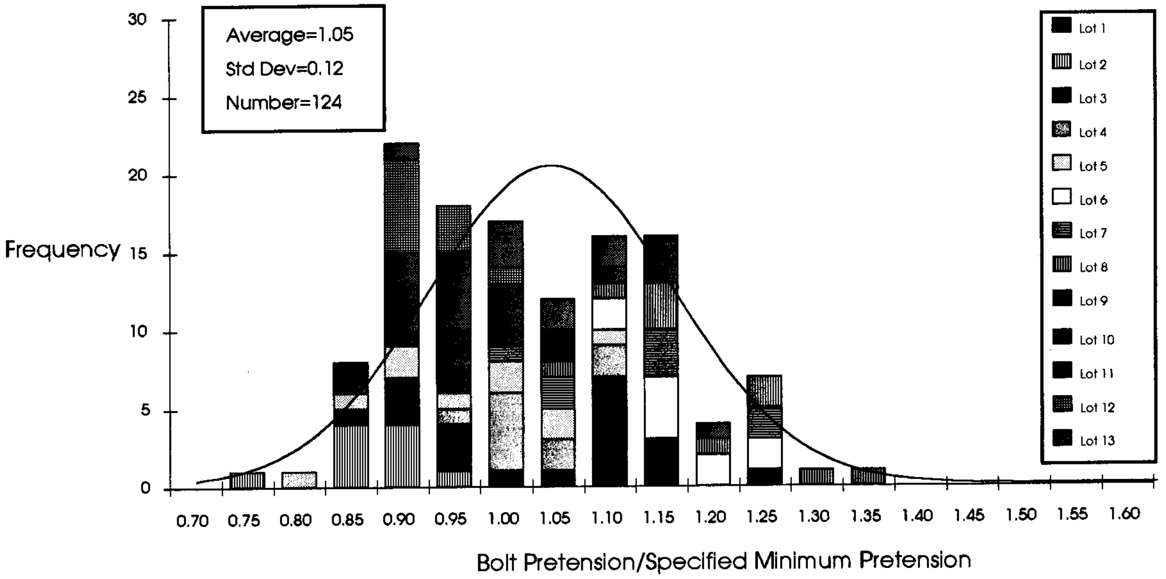


Fig. 4.15. Histogram of bolt pretensions for bolts weathered in a simulated steel joint for four weeks

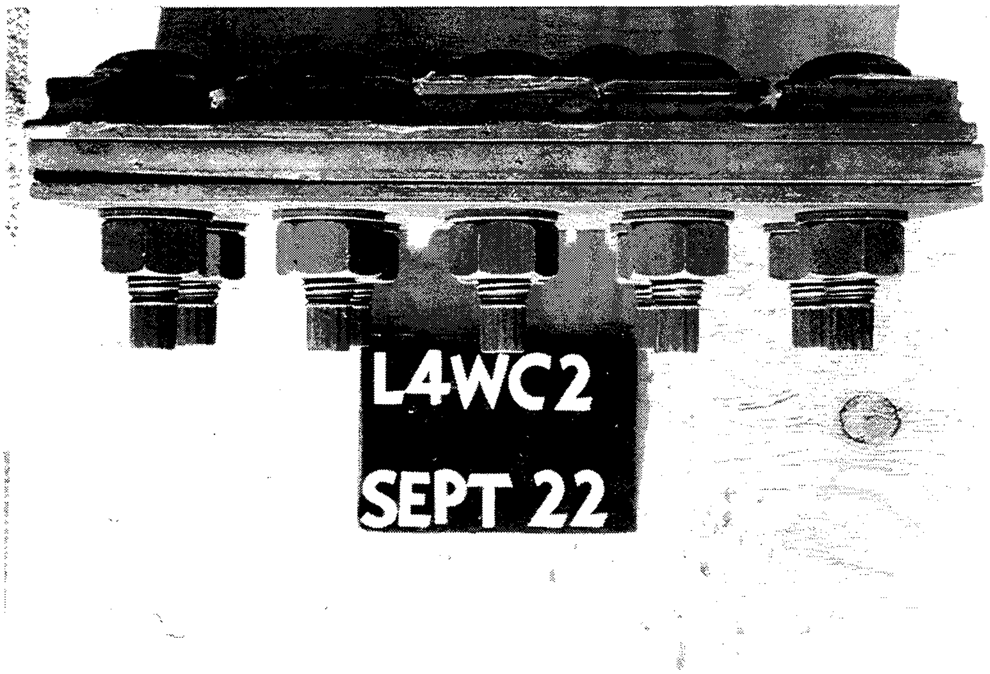


Fig. 4.16. Typical bolts after being weathered in a simulated steel joint for two weeks

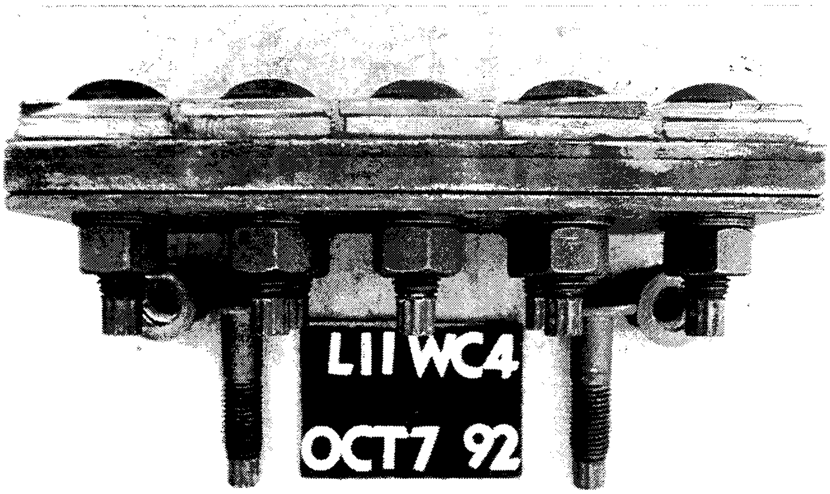


Fig. 4.17. Typical bolts after being weathered in a simulated steel joint for four weeks

5.0 SUMMARY AND CONCLUSIONS

5.1 Direct Tension Behavior and Hardness Measurements

The results from the direct tension tests show that the manufacturing of these bolts is as required, that is, the bolts are in accordance with the strength requirements for standard ASTM A325 bolts (4). This was expected. Likewise, the average hardness of the bolts tested meets the requirements for ASTM A325 bolts.

5.2 Torqued Tension Behavior

The torqued tension tests indicate that the behavior of these bolts in torqued tension is similar to that of standard A325 bolts. The bolts reached an ultimate load in torqued tension that was, on average, 12% less than the average ultimate strength in direct tension. Standard A325 bolts experience a reduction in the torqued tension ultimate load of 15%, on average (2).

The reason for the similarity in ultimate load capacity between a tension-control bolt and a standard bolt is that the type of test done on the tension-control bolts was quite similar to the torqued tension test that is used for standard bolts. With a standard bolt, the normal procedure is to measure load and elongations of the bolt after successive intervals of tightening the bolt with a wrench (e.g., an impact wrench). However, the tension-control bolts used in this program were tested in a slightly different fashion. For the tension-control bolts, the torqued tension test consisted of two parts. In the first part, which involved bolt loads and elongations up to the time of twist-off of the splined end, the tension-control installation wrench was used to tighten the bolt. In the second stage, a manual wrench was used to carry the bolt past the point of twist-off of the splined end. Thus, the only difference between a torqued tension test on a standard bolt and that on a tension-control bolt is that the tension-control bolt test employed the tension-control installation wrench up to the point of twist-off of the splined end. It had been speculated that by carrying out an installation as far as possible with a tension-control installation wrench, the ultimate load obtained by subsequently applying a manual wrench might be higher than that for a standard bolt with a manual wrench used for the entire tightening process.

5.3 Installation Characteristics and Delivered Pretension

The state of stress in a tension-control bolt is entirely direct tension in the region between the underside of the head and the underside of the nut. In a turn-of-nut installation, both tension and torsion are present in this region, however. Theoretically, then, it is possible to pretension the tension-control bolt to a higher level than if the same bolt were installed by turn-of-nut. In practice, however, the pretension that will be attained is controlled by the features provided as a result of the manufacturing process—the size of the twist-off groove, the conditions of lubrication, and the material strength. The test program reported herein used bolts as supplied by the manufacturers. As such, the dimensions of the twist-off groove, the quality and location of the lubrication, and the strength of the bolt were already established. The pretensions measured reflect the various conditions of thread damage, lubrication, intentional contamination of the threads, and different conditions of storage of the bolts.

In the reports of pretension that follow (Section 5.5), the figures reported are average values for all lots. Examination of Tables 4.17 and 4.19 will show that there can be significant variations between lots.

5.4 Installation Characteristics and Bolt Ductility

As already noted, the state of stress in the major portion of a tension-control bolt is entirely direct tension. In addition to potential higher bolt tensions, this state of stress should also allow for a larger deformation capacity than a standard bolt installed by turn-of-nut. This was neither proven nor disproved in this test program since the ductility measured partly reflected the instrumentation and type of test done. Regardless, the deformation capacity of tension-control bolts is mainly an academic issue: it is not likely that any field installation will be taken past the point of twist-off of the splined end.

5.5 Pretension

5.5.1 As-Delivered Bolts

The average normalized pretension of all of the bolts tested as-delivered in this test program was 1.20, standard deviation 0.11. As will be seen later, exposure to outdoor humidity and weather decreased this value.

The ages of the various bolt lots upon receipt was not constant. The ideal case would have been to have all lots of bolts lubricated by the manufacturer and then immediately shipped to the laboratory (excluding the lots that were purposely tested as being old). Examination of Tables 4.17 and 3.1 shows, however, that the bolt age may not necessarily be an issue. The second lowest average pretension obtained from all of the lots in the as-delivered condition came from Lot 13, which was only about one-half a month old upon receipt and for which the average normalized pretension was 1.12. The second highest average pretension for all lots in the as-delivered condition came from Lot 1, which was about 30.5 months old and for which the average pretension was 1.31. This shows that lubricant quality and durability is determining factor. (It should be noted that part of the difference in attained pretension between these two lots also stems from the fact that their average tensile strengths are somewhat different. Normalizing these average pretension with respect to the average tensile strength of their respective lots in direct tension (Table 4.7) shows that Lot 1 attained 75% of its average ultimate tensile strength, while Lot 13 reached 70% of its average ultimate tensile strength.)

The average normalized pretension for the individual lots ranged from 1.05 to 1.37. Lot 9, for which the pretension was 1.05, should be distinguished from the other lots because it consisted of 7/8 in. diameter bolts. All other lots were 3/4 in. diameter bolts. Also, it was readily apparent that Lot 9 had lost much its lubricant as the threads and washers appeared to be dry. Of the ten lots tested as-delivered, five attained pretensions greater than 1.20, four reached pretensions of between 1.12 and 1.17, and, as already mentioned, Lot 9 reached a pretension of only 1.05. This range of pretensions between bolts lots can be attributed to two factors: lubrication and, to a lesser extent, bolt strength. Lot 1 had an average measured ultimate strength to specified minimum ultimate strength ratio of 1.23, which is close to the average ratio reported for all lots (1.21). The strength ratio for Lot 11 was 1.20, also close to the average strength ratio for all lots. However, the average normalized pretension for Lot 1 was 1.31 while for Lot 11 it was 1.16. The difference here appears to be coming from the lubrication conditions and is more readily seen in the pretension to ultimate tensile strength ratios reported in Table 4.7. By dividing the measured pretension of a lot by its average tensile strength, strength variations are eliminated, leaving lubrication (or friction) conditions as the main variable. (The diameter of the annular twist-off groove could also be a contributing factor, but Table 4.1 shows that there is relatively little variation of the diameter within a lot and between lots.)

Bolt strength can also affect bolt pretension. Lot 2 attained an as-delivered pretension of 1.17, corresponding to 77% of its ultimate strength. Lot 1 reached a much higher pretension of 1.31, and this corresponds to only 75% of its strength, which is close to the value for Lot 2. This reflects the fact that Lot 2 had an ultimate tensile strength of 1.06 with respect to the minimum specified tensile strength, while Lot 1 had a strength ratio of 1.23.

Further discussion on the importance of lubrication is provided in Section 5.5.2.

5.5.2 Thread Damage, Lubrication, and Contamination Effects

Normal handling of metal kegs containing bolts did not appear to affect the installed pretension of the tension-control bolts in a significant way (Section 4.3.3). At some point, thread damage could certainly have an effect on the pretensions, but the damage imposed here did not.

Thread lubrication plays a significant role in determining installed pretension. If threads and washers are deliberately cleaned of the lubricant supplied by the manufacturer, friction levels will be high and the desired level of pretension is unlikely to be attained. The work reported in Section 4.3.3 (and summarized in Table 4.6) showed that when the tension-control bolts were deliberately cleaned, the average normalized pretension was 0.81. This is only 46% of the direct tension ultimate strength of the bolts. This average pretension is in sharp contrast to the as-delivered pretension of these bolts (1.31). Although re-lubricating the bolt threads and washer with lithium grease improved the level of pretension (to 1.14), it was still less than the pretension attained in the as-delivered condition. Re-lubricating the bolt threads and washers with thread compound produced a substantial increase in pretension, with an average value of 1.52. A pretension value of 1.52 means that 87% of the ultimate tensile strength of the bolts is being utilized in the pretension. Thus, it is readily apparent that the condition of lubrication on the bolts is a key factor in determining the pretension attained.

The work reported in Section 4.3.3 also showed that the frictional torque at the nut–washer interface accounts for as much as 90% of the total torque present. When the bolts were re-lubricated with lithium grease on the washer only (the threads remaining "dry") the normalized pretension was 1.07. Re-lubricating only the washers with thread compound produced a pretension of 1.33. This means that both the quality of the lubricant and its location on the elements of the bolt assembly are important.

Deliberate contamination of the threads of an as-delivered bolt did not have a large effect on pretension. When only the threads of the bolts were contaminated with dirt the pretension was 1.27, which is close to the as-delivered value (1.31). However, when the entire bolt assembly was contaminated (bolt, nut, and washer), the pretension was significantly lower (1.17). This second case supports the idea that the nut-to-washer interface lubrication is an important factor in determining pretension since in this case, the interface was contaminated, thereby increasing the friction at this location.

5.5.3 Indoor Storage

It was shown in this study that indoor storage in a sealed keg for four weeks does not cause any significant decrease in bolt pretension. However, as discussed in Section 4.3.4, bolt lot ages varied upon receipt .

Lower pretensions may result if bolts are stored indoors in either unsealed metal kegs or in cardboard boxes. (In this test program all the bolts were placed in sealed kegs once they arrived at the laboratory.) Unsealed kegs may have an effect on pretension since air would have direct contact with the lubricant on the bolts. This appeared to the case for the Lot 10 bolts, which were subject to long-term indoor storage, as described in Section 4.3.6. These bolts showed a considerable decrease in pretension after long-term indoor storage in an unsealed metal keg.

If the bolts are stored in something like a cardboard box, the cardboard may absorb the lubricant, thereby affecting subsequent pretensions. Cardboard boxes are probably not a typical storage container in the field, but some lots were received in this condition (see Section 4.3.1).

The average normalized pretensions for the as-delivered and the two and four-week indoor storage bolts were 1.20, 1.16 and 1.20, respectively. These lie between the reported values of pretension for the turn-of-nut and calibrated wrench methods (2). Also, the standard deviations for the bolts tested are comparable to the standard deviation for the turn-of-nut method, but higher than the standard deviations for the calibrated wrench method.

Long term indoor storage in an unsealed keg may be deleterious, as seen by the results for Lots 10 and 11 in the long-term indoor storage tests described in Section 4.3.6.

5.5.4 Exposure to Humidity

Exposing bolts to humidity for two and four weeks resulted in lower pretensions than for the as-delivered and the two and four-week indoor storage pretensions. The two and four-week average pretensions are 1.16, standard deviation 0.14, and 1.17, standard deviation 0.13, respectively. The slight increase in pretension from the two-week test to the four-week test must be attributed simply to pretension variability.

These pretensions are slightly better than those reported for the calibrated wrench method of installation, but are significantly less than those obtained by the turn-of-nut method (2). The standard deviation of pretensions for the bolts tested is slightly larger than that for the turn-of-nut method. Exposure periods longer than two to four weeks can be expected to lead to even lower pretensions. Higher levels of relative humidity than those reported for this program will also likely lead to further decreases in pretension.

5.5.5 Bolts With Full Exposure to the Weather

Subjecting individual bolts to full exposure to the weather has a significant effect on attained pretensions, as seen in Section 4.3.8. The two and four-week average pretensions are 1.12 (standard deviation 0.11) and 1.10 (standard deviation 0.11), respectively.

The average pretensions here are slightly less than those reported for calibrated wrench installations and are less than the pretension obtained from tension-control bolts that were exposed to humidity. The standard deviations are comparable those obtained when the turn-of-nut method is used. Weathering that is more harsh than what was experienced in this program is certainly possible. The bolts did rust, but less than might normally be expected for the periods of time involved. The amount of rust and lubricant degradation will vary along with attained pretension, of course, depending on the local climate.

5.5.6 Simulated Joints

Tension-control bolts in the simulated joints provided the lowest bolt pretensions of all the different types of exposures. The two and four-week average pretensions are 1.05 (standard deviation 0.10) and 1.05 (standard deviation 0.12), respectively.

These pretensions are obviously close to the specified minimum pretension. The pretensions are lower than those reported for calibrated wrench installations, and very much lower than those obtained by turn-of-nut installations.

5.6 DISCUSSION AND CONCLUSIONS

5.6.1 Slip Probability and Slip-Critical Relationships

In the case of a slip-critical joint, the probability of slip is a reflection of both the slip coefficient of the connected material and the clamping force provided by the bolts. Both quantities have a dispersion about their mean value. Thus, the actual slip probability depends on the method used for bolt installation and on the condition of the faying surfaces in the joint.

The equation for the slip resistance of a joint given in the *Guide* (2) is:

$$P_s = m\, n\, \alpha\, T_{ispec}\, k_s \tag{5.1}$$

where

P_S = slip load
m = number of slip planes
n = number of bolts
$\alpha = T_i / T_{ispec}$
T_{ispec} = specified minimum pretension
k_S = slip coefficient of the connected material

Equation 5.1 is not suitable for design purposes since the designer is unlikely to be able to establish values for α and k_S nor be able to incorporate the variation from the mean of each of those quantities. The *Guide* addresses this by providing the following expression for slip load:

$$P_s = D\, m\, n\, T_{ispec}\, k_{s_{mean}} \tag{5.2}$$

where, "D is a multiplier that provides the relationship between $k_{s_{mean}}$ and k_S, incorporates α, and reflects the slip probability level." The *Guide* provides values of D for a variety of cases. For example, if the mean slip coefficient is 0.33 and A325 bolts are installed using the turn-of-nut method, then a value of D = 0.820 reflects a slip probability level of 5%. For the same conditions except that a calibrated wrench installation is used, D = 0.718 must be used for a 5% slip probability. The *Guide* (2) provides values for D for slip probabilities of 1%, 5%, and 10% for values of slip coefficient ranging from 0.20 to 0.60 and for both turn-of-nut and calibrated wrench installations using either A325 or A490 bolts. A total of 54 values of D are thus tabulated.

The RCSC Specification has adopted Equation 5.2 as the basis for its design rules. However, in the interest of simplicity the number of values given for D is greatly reduced. As a consequence, the slip probability is not a constant for a given installation method. The values of D given in the RCSC Specification provide a slip probability of 5% when the turn-of-nut method is used, but it will be 10% when the calibrated wrench method is used.

5.6.2 Comparison of Tension-Control Bolt Installations to the Turn-of-Nut and Calibrated Wrench Methods

As noted in Section 1.2, the turn-of-nut method of installation provides normalized bolt pretensions of 1.35 with respect to the specified minimum pretension (standard deviation of 0.12) for A325 bolts installed to one-half turn in laboratory experiments. However, as described in Section 4.1.1, the actual pretension in the field may be less. The calibrated wrench method gives pretensions 1.13 (standard deviation of 0.06). In this case, only laboratory studies are available. It seems reasonable to expect that the pretension attained by any installation method (e.g., tension-control bolts, load-indicating washers) should attain pretensions that are at least as high as those reported for the calibrated wrench installation. Otherwise, specifications would have to make it clear that a greater probability of slip exists for these cases.

5.6.2.1 As-Delivered and Indoor Storage bolts

The tension-control bolts that were tested in the as-delivered condition, after indoor storage in a sealed keg, and after exposure to ambient, indoor humidity had average pretensions that were between the average pretensions produced by the turn-of-nut and calibrated wrench methods. The lowest average value of measured pretension to specified minimum pretension in any of these categories was 1.16 (Table 4.16). It must be noted, however, that a few individual lots were much lower than this.

5.6.2.2 Bolts Exposed to Humidity

Exposure of the tension-control bolts to outdoor humidity provided pretensions that were slightly better than those provided by the calibrated wrench method in a laboratory environment, but much less than the pretensions obtained from the laboratory turn-of-nut method results. Compared to the turn-of-nut installations in the field (5), the tension-control bolt pretensions here can be substantially less. The lowest average pretension measured was 1.16 with respect to the minimum specified pretension (Table 4.16). However, some of the individual lots attained pretensions that were in the region of 1.03 (Table 4.17).

5.6.2.3 Bolts Given Full Exposure to the Weather

The tension-control bolts that were given full exposure to the weather gave pretensions that are marginally lower than those delivered by the calibrated wrench method. After two and four weeks of exposure, the tension-control bolts gave average pretension to specified minimum pretension ratios of 1.12 and 1.10, respectively (Table 4.16). As in all of these comparisons, the results for the individual lots should also be examined (Table 4.17). Of the 23 lots in this category, five showed values of the pretension ratio less than 1.0 and eleven lots were less than the figure 1.13 that pertains to calibrated wrench installations. However, field studies of bolts installed by calibrated wrench are not available, and the comparison with tension-control bolts should be viewed in that light.

5.6.2.4 Bolts Weathered in a Simulated Steel Joint

The tension-control bolts that were weathered in the joints prior to final installation produced pretensions that were much lower than those that would be obtained by the calibrated wrench method and very much lower than those for the turn-of-nut method in a laboratory environment. After two and four weeks of exposure, the average pretension ratio was 1.05 in both of these cases (Table 4.16). Eight of the 23 lots tested attained pretension ratios that were less than 1.0, while another six reached pretensions ranging between 1.00 and 1.05. In total, 16 lots gave pretension ratios that were much less than the calibrated wrench method ratio of 1.13. Overall, the pretensions seem to be much less than the field pretension of standard bolts installed in bridges using the turn-of-nut method (5).

Installation of tension-control bolts in a way comparable to that used in the weathered joint tests, that is, installing bolts in a joint with a snug-tight load in the bolt, and then later (two or four weeks) performing the final tightening, means that the majority of the tension-control bolt joints will have a pretension that is less than that for bolts installed by calibrated wrench. Furthermore, recalling that the average pretensions for the two and four-week weathered joint tests were both 1.05, with standard deviations of 0.10 and 0.12, it is quite likely that a significant number of joints in the field that use tension-control bolts will have a clamping force that is even less than the specified minimum value, that is, a ratio of measured pretension to specified minimum pretension less than 1.0. As previously noted, eight of the individual 23 lots in this category had values of this ratio less than 1.0.

5.7 CONCLUSIONS

Based on the results reported herein, the following conclusions can be stated:

1. The tension-control bolts supplied for this program met the mechanical requirements of ASTM Specification A325–92a.

2. The expectation that tension-control bolts will be loaded entirely in direct tension upon installation of the bolt with a tension-control installation wrench holds true up to the point of twist-off of the splined end of the bolt. To induce any further tightening requires the use of a conventional wrench (e.g., an impact wrench), and this results in torsion stresses being introduced in the shank of the bolt. These torsional stresses reduce the tensile capacity of the bolt and the ultimate load closely compares with that of a standard bolt tightened exclusively with a conventional wrench.

3. Normal handling of metal kegs containing bolts did not affect the installed pretension of the bolts in a significant way.

4. The as-delivered pretensions of the tension-control bolts fall between the pretensions reported for laboratory studies of standard A325 bolts installed by turn-of-nut and by calibrated wrench.

5. Thread and washer lubrication are important to the performance of tension-control bolts. Torsional friction at the nut–washer interface accounts for as much as 90% of

the total torsional friction. Thus, proper lubrication of the washer is a crucial factor for the attainment of pretension.

6. Cleaning as-delivered bolts of the lubricant that is supplied by the manufacturer results in unacceptable pretensions when the bolts are installed. Re-lubricating the bolt threads and washers with a multi-purpose lithium grease allows the installed pretension to rise, but not to the pretension level of as-delivered bolts. Re-lubricating the bolts with thread compound allowed the bolts to attain very high pretensions, exceeding the as-delivered pretensions by a significant margin.

7. Contamination of the bolt threads with soil resulted in a small decrease in pretension. Contamination of both the threads and washer of a bolt caused a moderate decrease in pretension.

8. Bolts stored indoors in a sealed metal keg for short periods (two and four weeks) produced pretensions that are comparable to those for as-delivered bolts.

9. Depending on the age of a bolt at the start of a storage period, long-term indoor storage can have an effect on installed pretension. Bolts that were reasonably old at the start of the storage period (two years old) did not show a decrease in pretension after an extended period of indoor storage (six months) in a sealed metal keg. Newer bolts (initially $2-1/2$ months old) did seem to provide lower pretensions after this type of storage. Bolts stored in an unsealed keg attained lower pretensions than when as-delivered.

10. Exposure to outdoor humidity for two and four weeks reduced the pretension of a tension-control bolt compared to its as-delivered pretension. Generally, the pretension after two or four weeks of exposure was comparable to that for standard bolts reported in laboratory studies for the calibrated wrench method (2). However, some bolts attained a pretension that was less than that for the calibrated wrench method, and in fact, less than the specified minimum pretension (although the latter case did not

occur very often). And, of course, a few bolts exceeded the average calibrated wrench pretension by a significant margin.

11. Allowing bolts to be fully exposed to the weather for two or four weeks generally resulted in pretensions that are somewhat less than those provided by the calibrated wrench method (2) and significantly less than those produced by the turn-of-nut method as reported in laboratory studies (2). The tension-control bolt pretensions in this category of exposure are generally less than the reported pretensions of standard bolts installed by turn-of-nut in the field (5). In this type of exposure, more bolts had pretensions that were less than the specified minimum pretension as compared with bolts that were exposed to the outside humidity for two and four weeks.

12. Exposing bolts to the weather while snug-tight in a joint for two or four weeks is the most detrimental type of exposure considered in this study. The average bolt pretension after the exposure was only marginally greater than the specified minimum pretension. The pretensions measured here was less than those produced by the calibrated wrench method (2) and substantially less than those produced by the turn-of-nut method (2). They were also much less than the pretensions reported for field installations of A325 bolts in bridges by turn-of-nut (5). Almost one-third of the bolt lots tested in this condition gave pretensions that were less than the specified minimum pretension.

This test program has illustrated that the performance of a tension-control bolt is strongly a reflection of the conditions of friction that exist on bolt threads and the washers supplied with the bolts. As the quality of the lubricant decreases, resulting in a higher coefficient of friction between the bolt and nut threads and at the nut–washer interface, the installed pretension also decreases. Furthermore, as the durability of the lubricant supplied decreases, the pretension attained after a given exposure type and length of time will also decrease. Superimposed on top of this is the fact that the majority of frictional torque occurs at the nut–washer interface. If a proper amount of lubrication is not maintained on the washer (or the washer side of the nut face), clamping force will be less than otherwise. Since the pretension attained is also dependent on the type of exposure, specific installation techniques may have to be dictated by specifications. Thus, proper manufacturing in combination with proper installation is required in order for this fastener system to perform satisfactorily in field installations.

With all of these results in mind, it should be noted that achieving a pretension that is simply equal to the specified minimum pretension in *any* high strength pretensioned bolt installation should not be the goal of the erection crew, nor of the fastener manufacturer. The philosophy of the design procedure given in the RCSC Specification is not based on achieving simply the specified minimum pretension, it is based on achieving a pretension that exceeds the specified minimum pretension by a given margin. In a turn-of-nut installation this margin is 35%. For the calibrated wrench method the margin is 13%. The difference in these two margins is reflected in the slip probability levels—5% for turn-of-nut and 10% for calibrated wrench. If a joint is clamped together with bolts that are pretensioned to the specified minimum pretension on average, the slip probability will be greater than 10%. Thus, in order to produce quality pretensioned joints, bolts should installed to reach a pretension that is at least comparable to that produced by a calibrated wrench, but, preferably, to the level attained in a turn-of-nut installation.

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