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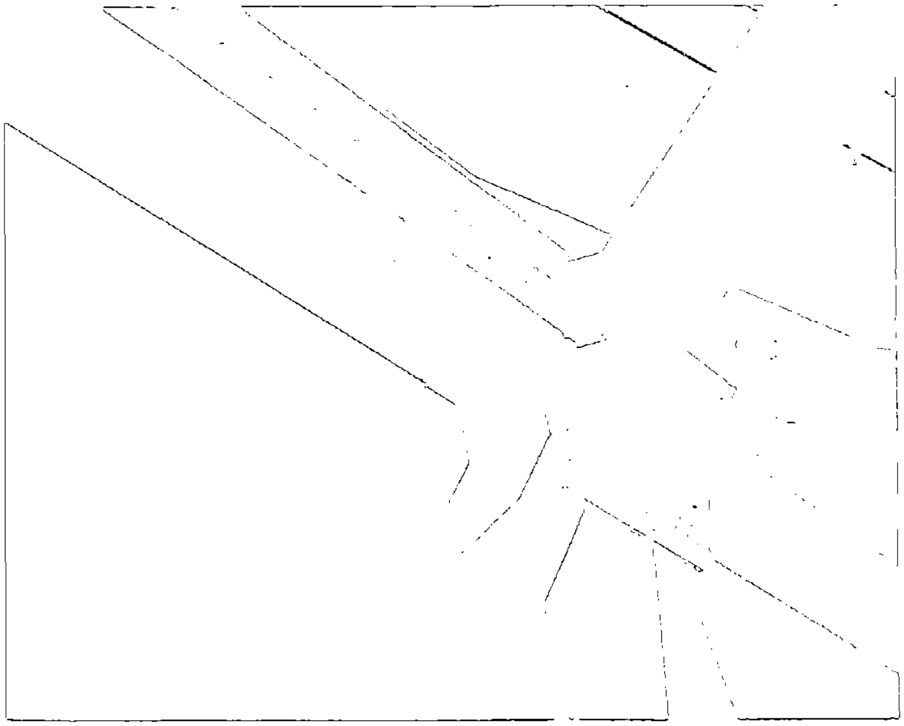
High Strength Bolts for Bridges



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Federal Highway Administration

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FOREWORD

This report "High Strength Bolts for Bridges" presents the results of research conducted by the University of Texas at Austin for the Federal Highway Administration (FHWA), Office of Engineering and Highway Operations Research and Development under contract number DTFH61-85-C-00174.

The research was conducted to verify or improve our determination of bolt tension and bolt installation criteria and insure that proper design values of bolt tension are maintained when installing high strength bolts.

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Thomas J Pasko

Thomas J. Pasko, Jr., Acting Director
Office of Engineering and Highway
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NOTICE

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16. Abstract

An extensive experimental program was conducted to evaluate the performance of both black and galvanized high strength bolts for bridges. Seventy-two A325 black bolts, 145 hot-dip galvanized A325 bolts, 85 mechanically galvanized A325 bolts, and 83 black A490 bolts from several different suppliers, were tested under direct and torqued tension in order to evaluate the current installation practices and ASTM Standard requirements for high strength bolts and to develop guidelines which will ensure proper installation and satisfactory performance of these bolts. An important parameter in the test program was the thread conditions of the bolts and nuts. Four thread conditions were examined: as-received, cleaned, weathered and lubricated. Several types of lubricants were considered in the course of the experimental program.

The results indicate that a great deal of the problems associated with the performance of high strength bolts lies in the vagueness of the current ASTM Standards and the failure of the bolt suppliers to follow the requirements stated in these standards. A major recommendation in this study is to establish a unified standard which will cover the performance of fastener assemblages (bolt-nut-washer) under the responsibility of one committee. Guidelines for proper installation of high strength bolts are also given.

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NOMENCLATURE

A_a = tensile stress area used in Alexander's model [Eq. 4]

A_{sb} = shear area of bolt threads

A_{sn} = shear area of nut threads

B_s = bolt stripping load

d = minor diameter of nut; the smaller of d_n or d_w

d_n = measured minor diameter of nut on identification side

d_w = measured minor diameter of nut on the washer side

D = major diameter of bolt threads, nominal diameter of bolt

D_s = shank diameter of bolt

F = width across flats of the nut

F_b = bolt ultimate tensile stress based on A_a

F_n = nut ultimate stress based on hardness

F_u = experimental bolt ultimate tensile stress based on nominal tensile stress area

H = nut height

H_b = height of the bell-mouthed section of the nut

K = dimensionless nut factor

L = threaded length of bolt

P = tension in the installed bolt

N_s = nut stripping load

P_u = measured bolt tensile strength in kips

R_B = Rockwell hardness - B scale

R_C = Rockwell hardness, C scale

T = Torque

z_b = average zinc thickness on bolt

z_n = average zinc thickness on nut

CHAPTER 1. INTRODUCTION

Problem Statement

High strength bolts in field connections for bridges require substantial installed tension, also called clamping force or bolt preload. The minimum specified tension is 0.7 of the ultimate strength.[27] The attainment of this level of preload requires careful attention to installation procedures and material specifications. In spite of thirty years of experience with high strength bolted construction, there continues to be problems with the proper installation of these fasteners. This is especially true for galvanized bolts. An experimental research program was undertaken to examine problems associated with the development of the proper preload in high strength bolts. Before discussing the objective and scope of this experimental research, methods of bolt installation will be described along with a summary of specific bolt installation problems.

Bolt Installation Practice

Two types of high strength bolts are permitted in building and bridge construction, ASTM A325 and A490. A listing of American Society for Testing and Materials (ASTM) and American National Standards Institute (ANSI) publications used in this report is given in appendix A. The bolt, nut, and washer materials are covered under ASTM specifications and their manufacturing dimensions and tolerances are controlled by ANSI standards. The required preload, installation methods, and inspection of the installed fasteners in structural joints are covered by the Specification for Structural Joints Using ASTM A325 or A490 Bolts or simply called the Bolt Spec throughout this report.[27] The AASHTO M164 and M253 specifications correspond to the ASTM A325 and A490 specifications, respectively. The ASTM designation will be used throughout this report since bolt head markings conform to this standard.

Hex head bolts can be installed by the turn-of-nut method or by calibrated wrench. The Research Council on Structural Connections (RCSC) has spent considerable effort in identifying the critical factors that affect these two tightening methods and in developing specific requirements for each method to ensure proper bolt tension. The detailed requirements are given in the Bolt Spec. In both methods enough bolts must be installed in the joint to bring the component plates in firm contact which is called the snug tight condition. Following the snug tightening operation, bolts are tightened further by an additional prescribed rotation in the turn-of-nut method. Washers are not required except in certain conditions with A490 bolts. Care must be taken that one end of the fastener is prevented from rotating while tightening the bolt.

In the calibrated wrench method, wrenches are set to provide a tension not less than 5 percent higher than the minimum specified tension. The calibration is accomplished by inserting a bolt in a device capable of indicating bolt tension, most commonly a Skidmore-Wilhelm calibrator. The wrenches must be set each day and for each bolt diameter length and grade. Actually, the wrench should be set for each lot of bolts. Since this tightening method relies on torque control, variations in thread condition should be noted and the wrenches recalibrated if surface conditions change. A washer must be used at the bolt head or the nut, whichever is turned.

Spline end bolts (twist-off bolts), which are supplied with a nut and washer, are permitted by the Bolt Spec. A special wrench holds the spline end while the nut is tightened. With this type fastener, the spline will twist off when the tension reaches at least 5 percent above the minimum specified. These bolts depend on a reliable tension-torque relationship, so thread conditions and lubrication must be controlled by the manufacturer. The manufacturer's certification usually shows the tension reached for a sample of three to five bolts. This fastener system has gained significant popularity in the past few years with about 60 percent of building projects now using them.

Load indicator washers under ASTM F959 can be used to verify that the minimum preload has been installed. The protrusions on the washer are calibrated by the manufacturer to compress inelastically so that a specified gap remains at minimum specified bolt preload.

The latest Bolt Spec dated Nov 1985 provides very detailed installation procedures including fastener storage requirements. The presentation is greatly expanded from that in previous editions. (The provisions in the new Bolt Spec have been incorporated in the 1987 AASHTO Bridge Specification currently under ballot.) A tension-indicating bolt calibrator is now required at the job site so that the bolt-nut assembly can be shown to provide the required tension, to check out bolt crews on proper installation procedures and load indicator devices, and to calibrate impact and inspection wrenches. It is also made clear that the proper installation procedures must be verified by on-site inspection. Post-installation inspection through the use of twist-off bolts or load-indicating washers do not provide evidence that the proper preload is present, as sometimes claimed by suppliers of these products. Proper tension will only be present if the connection is snugged up properly, which may require repeated snugging, and the bolts are tightened, starting from the most rigid part of the joint toward the free end.

The Commentary to the Bolt Spec, which was drafted by William Milek, Chairman of the Specification Committee of the RCSC, gives explanations of the installation and inspection provisions.[27] This well written document should be consulted for more details.

Fastener Installation Problems

Building inspectors, fastener product manufacturers, engineers, fabricators, suppliers, and the published record were consulted, along with the authors' own experience, to document bolt problems not associated with connection loads. A listing of these problems follows. But, it is also our perception that most production lots of black A325 bolts perform satisfactorily.

A. Black A325 Bolts and Nuts

- Stripping.
- Improper certification.
- Improper head and nut markings.
- Bolt breaking before proper preload.
- Bolt breaking before required turns.
- Overtightening of short length bolts.
- Soft nuts.

B. A490 Bolts

- Hardness out of specification.
- Hydrogen embrittlement after installation.
- Stripping.
- Bolt breaking before required preload.
- Bolt breaking before required number of turns.
- Improper certifications.
- Improper nuts.
- Galvanized A490.
- Longitudinal cracks in the bolts.

C. Galvanized A325 Bolts

- Stripping.
- No lubricant on nut.
- Unable to tighten bolt because of high torque.
- Misinterpretation of nut overtap requirements.
- Mixing of hot dip and mechanically galvanized products.
- Breaking of bolts at head, shank intersection.
- Improper zinc thickness.
- Bolt breaking before required number of turns.
- Bolt breaking before required preload.
- Threads out of tolerance.
- Inability of the nut to turn on to the bolt.
- Fastener components not shipped in one container.

- Improper galvanized nuts.
- Failure to satisfy the turn test.

D. General Problems for All Bolts

- Inadequate storage of on-site bolts.
- Bolts in rusted or dirty conditions.
- Certifications do not match bolts delivered.
- Counterfeit fasteners.
- Improper snugging.
- Improper tightening of the connection.
- Improper tightening of the bolt.
- No on-site inspections during tightening.
- Deliberate abuse of spline end bolts and tension-indicating washers.
- Inadequate knowledge of ASTM and RCSC fastener specifications by manufacturers, suppliers, engineers, contractors, and inspectors.
- No calibration of torque wrenches.
- Inadequate quality assurance programs.
- Poorly written specification provisions.
- "Foreign" bolts and nuts.

Most of the problems cited above are not new and specification provisions are in place to deal with them. "Foreign bolts" were frequently blamed for what appears to be an increasing problem with field installation. Very little documentation is available, however, and in many instances the shift of blame to foreign competition is self-serving. The fact is there is presently less than a handful of U.S. bolt manufacturers and only one nut manufacturer, so most of the bolts used on U.S. construction projects are of foreign manufacture. This is especially true for the twist-off bolt which building inspectors claim has resulted in a decrease in the number of bolts rejected because of insufficient tightening. It has also been noted by the authors that the competition among the various manufacturers of fastener products is so severe that public claims of inadequate performance of a competitor's products are blown out of proportion, thus making it more difficult for engineers to have confidence in high strength bolted construction.

Scope and Objectives

The purpose of this research was to study past work and conduct new experiments which might lead to a more reliable specifications to ensure adequate bolt performance in the field. The study focused on hot dipped galvanized and mechanically galvanized A325 bolts, but black A325 and A490 were also studied. Fit between the nut and bolt and types of lubrication were the primary variables considered. All bolts were purchased on the open market and all bolts (not nuts) were of U.S. manufacture, so that the U.S. vs foreign bolt controversy could be addressed. Hundreds of experiments using replicate samples for statistical reliability were conducted to establish the effect of the variables on the tension-torque-number of turns relationship of the bolt-nut-washer assemblage. The tension-torque-turns relationship is the principal factor for determining the level of preload to be expected in a properly tightened connection.

In chapter 2, important past studies which have been used in the development of the current ASTM, ANSI, and RCSC specifications and standards are reviewed. The current specifications are critiqued in this chapter. Chapter 3 describes experimental methods and fastener material properties used in the tests reported herein. Chapter 4 contains the bulk of the experimental studies conducted as part of this research program. A field test was conducted on the fasteners in a bridge which is currently in service to determine the level of installed preload in galvanized A325 and black A490 high strength bolts. The last chapter gives the suggested changes that should be implemented by bolt manufacturers, suppliers, engineers, and code writing bodies to improve the reliability and confidence in high strength bolted construction.

CHAPTER 2. BACKGROUND

In this section, past research studies and current specifications are reviewed for factors and provisions which affect the characteristics of installed bolts. A general summary of research on bolts and bolted connections is given in the Guide to Design Criteria for Bolted and Riveted Joints by Fisher and Struik.[13] The summary in this chapter will concentrate on A490 bolts, galvanized A325 bolts, highlights of specifications, lubrication and stripping.

Nomenclature

The nomenclature on fasteners used throughout this report is given in figures 1, 2 and 3, and at the end of the report. The basic Unified Coarse Thread (UNC) profile is shown in figure 1. For bolts, the external diameter of the threads is denoted as D and for nuts, the minor diameter, d, is measured. The difference between these two dimensions, h_e, determines the amount of thread engagement length (interface) shown in figure 2. Thread stripping potential is principally controlled by h_e; the smaller the value of h_e, the lower the stripping strength. The threaded length of the bolt, L, shown in figure 3 is measured from the first full thread to the end of the bolt. Frequently, nuts have a bell mouthed threaded zone, so the diameter at both ends of the nut and the depth of the bell mouth are necessary to define the thread profile.

General Behavior of Black Bolts

The behavior of a bolt-nut-washer assembly is characterized by what is commonly called a calibration curve, in which tension induced by the tightening process is plotted against bolt elongation or the number of turns of the nut. A calibration curve taken from a 1959 report is shown in figure 4.[5] Failure occurs by either bolt fracture or stripping of the bolt or nut. The shape of this curve depends on a variety of factors such as the strength

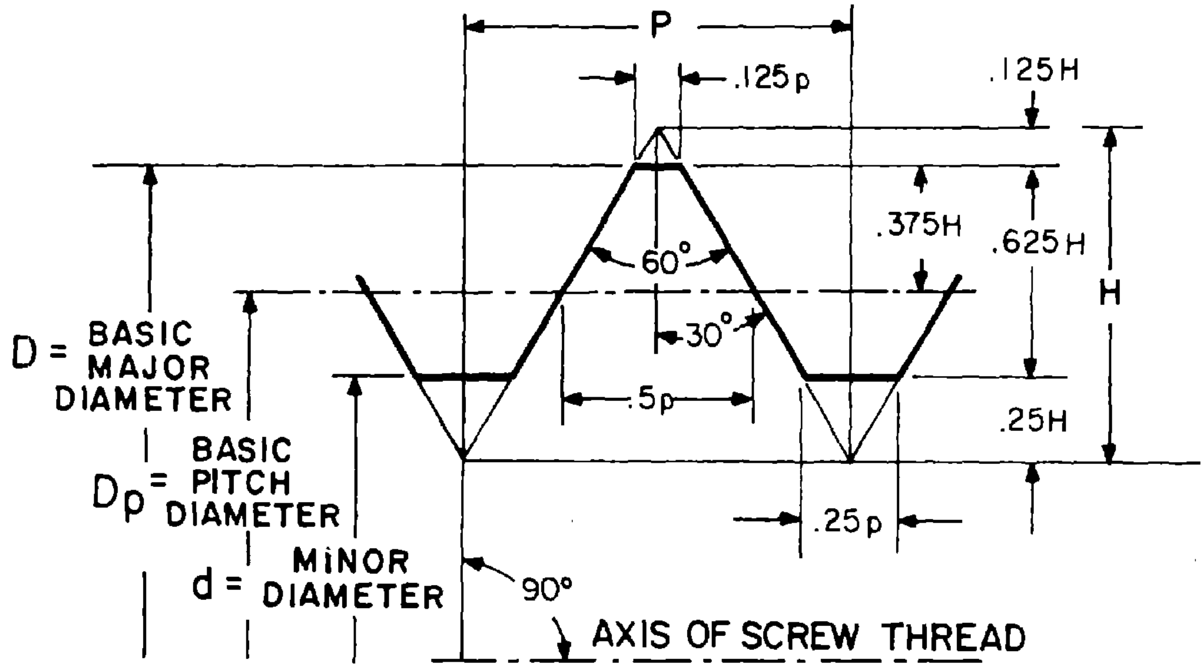


Figure 1. UNC basic thread profile from ANSI B1.1.

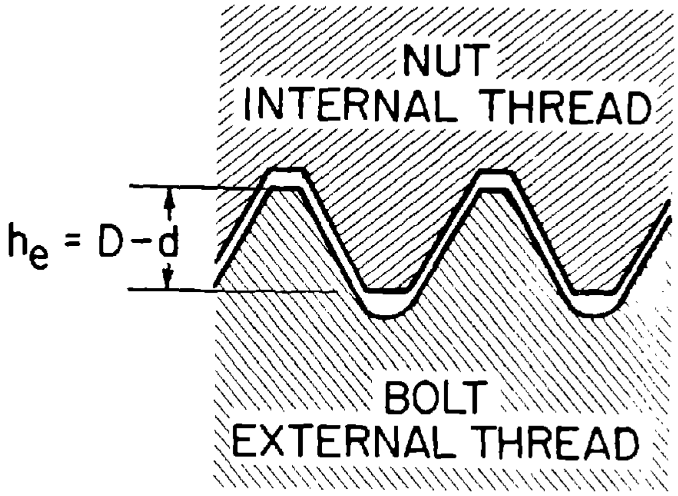


Figure 2. Depth of thread engagement (interface).

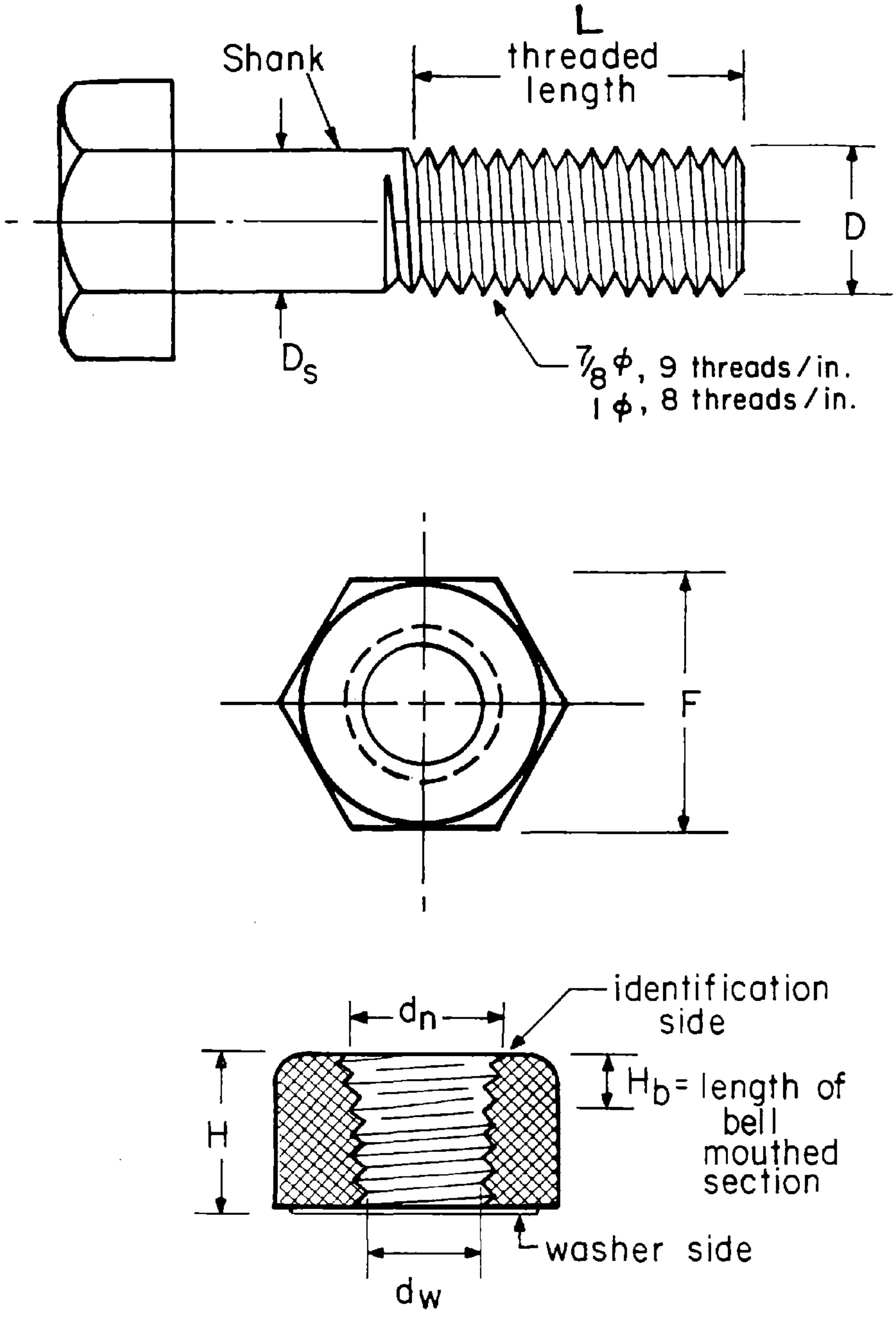


Figure 3. Nomenclature for bolts and nuts.

and ductility of the bolt material, nut strength, thread engagement length, lubrication, and number of threads in the grip.

Effect of Thread Length. The effect of different thread lengths within the grip are shown in figure 5 for three bolts with the same overall length. The grip is the total thickness of material between the head of the bolt and the washer face of the nut, exclusive of washers. As the thread length within the grip decreases, the maximum strength increases but the ductility decreases. Lot Q in figure 5 had the same thread length and bolt properties as the Lot Z bolts in figure 4. The 2-in (51 mm) thread length was the standard in the 1950's and it corresponds to twice the bolt diameter plus 1/4 in (6 mm). This thread length is currently standard for heavy hex bolts (ASTM A307 bolts), and is also standard for high strength bolts in Europe. In the U.S., however, the thread length on A325 and A490 bolts was shortened in 1960 to accommodate a "balanced joint design" concept for shear connections which required the full gross area shear strength of the bolt.[4,6] The shortened thread length bolt was called a heavy hex structural bolt and is the style used currently. The shear strength of the threaded portion was approximately 15 percent less than for the gross section so the thread length was decreased to eliminate threads in the shear plane expect in cases where the outside plies of plate material were less than 3/8 in (10 mm).[4]

The thread length of a U.S. 7/8-in (22 mm) A325 or A490 bolt is 1-1/2 in (38 mm) so it should show higher strength and less ductility than the Q bolts in figure 5. Interestingly, the "balanced joint design" concept was not adopted as a standard method. The current standard heavy hex structural bolt with the short thread length will normally provide between 3/8 and 5/8 in (10 and 16 mm) of thread within the grip so about two turns to failure would be expected for A325 bolts according to figure 6 taken from reference 29. If only one thread remains in the grip, failure can occur at one turn as shown in figure 7.

This detail on the effect of threads within the grip on bolt ductility has been presented because it can be mistakenly implied that current bolt

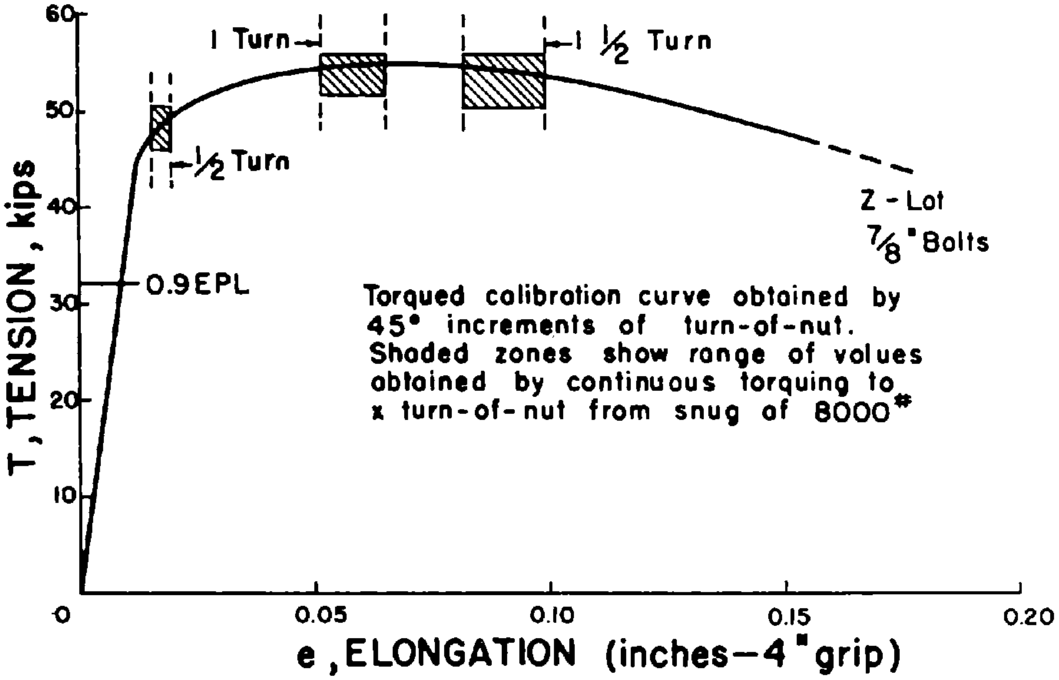


Figure 4. Tension-elongation relationship - A325 bolt.[5]

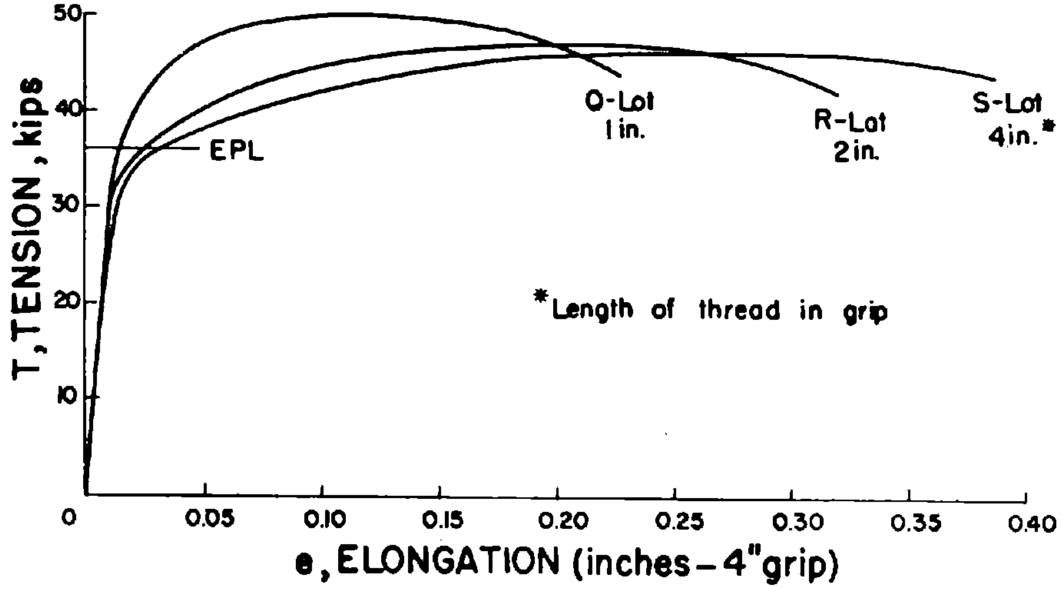


Figure 5. Effect of thread length in grip area.[5]

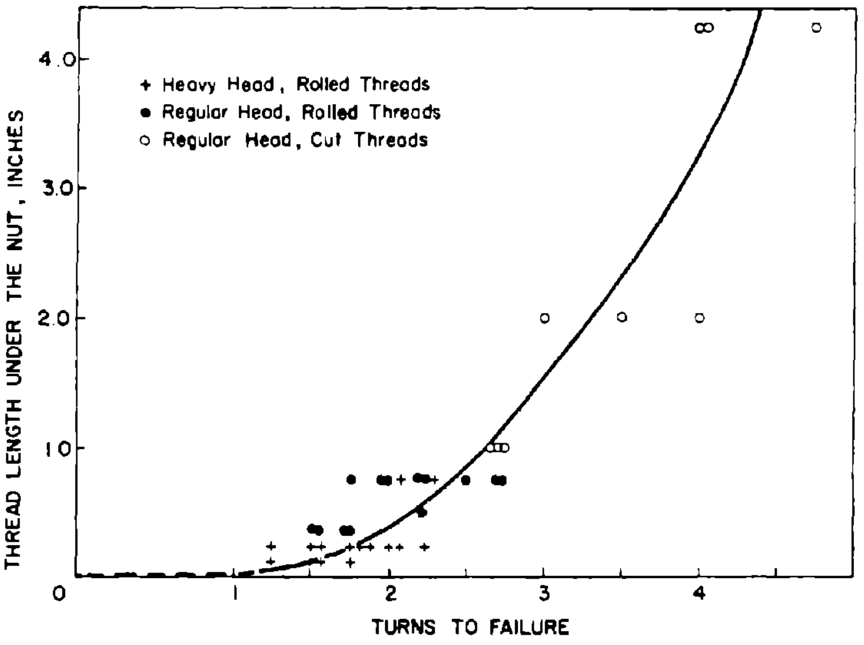


Figure 6. Effect of thread length on turns to failure.[29]

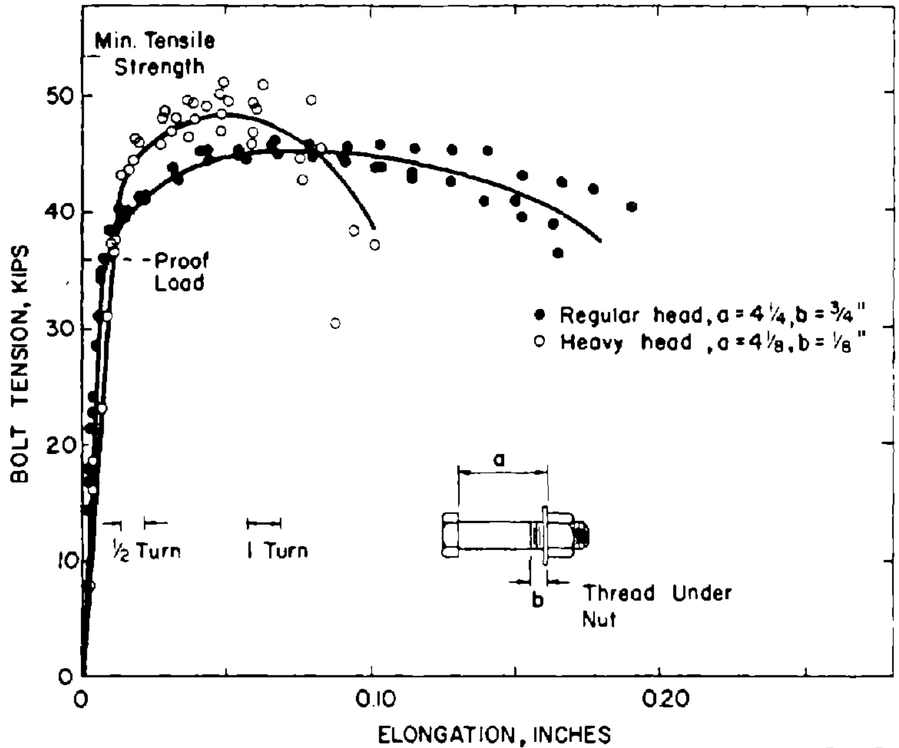


Figure 7. Reduced ductility for one thread in grip.[29]

material ductility is less than that in early studies rather than due to a difference in thread lengths, as shown. Also, the increased tensile strength associated with fewer threads in the grip increases the possibility of nut stripping. The minimum nut proof loads were established in the 1950's when bolt strengths were lower due to longer thread lengths.

Bolt Strength. A490 bolts have reduced ductility in a torqued-tension test compared to A325 bolts as shown in figure 8. The tension corresponding to a one-half turn from a snug load of 10 kips (44.5 kN) is also shown. The test was done in a Skidmore-Wilhelm hydraulic bolt calibrator as in the tests presented in figures 4 through 7. The minimum specified installed tensions by the current Bolt Spec and AASHTO Specification are 39 kips (173 kN) and 49 kips (218 kN) for A325 and A490 bolts respectively.[39] These requirements, which are 70 percent of the minimum tensile strength, are different from those in effect in 1965 when the required tension was equal to the proof load.

For A490 bolts, the decrease in tension after the maximum tension is reached is quite rapid compared to the unloading experienced in A325 bolts. The average turns to failure for the bolts in figure 8 were 1-1/3 turns. Turns to failure as high as 1-7/8 turns have been reported for A490 bolts.[12] Test results for a single lot of A490 bolts tested both at Lehigh University and the University of Illinois, shown in figure 9, suggest that the performance of A490 bolts is even more sensitive to the number of threads in the grip than previously shown for A325 bolts.

Type of Test Setup. Most calibration tests have been conducted in a hydraulic bolt calibrator which has less stiffness than the solid plates encountered in practice. If the bolt calibration curve is based on measured bolt elongation, there is no difference in performance. There is a difference between the two setups when nut rotation is used to calibrate rather than bolt elongation. Nut rotation is a useful measure of performance since the turn-of-nut installation method relies on nut rotation to control bolt strain. A typical comparison of the two setups is shown in figure 10 for the heavy hex structural bolt with short thread lengths. In the solid plate the A490 bolt

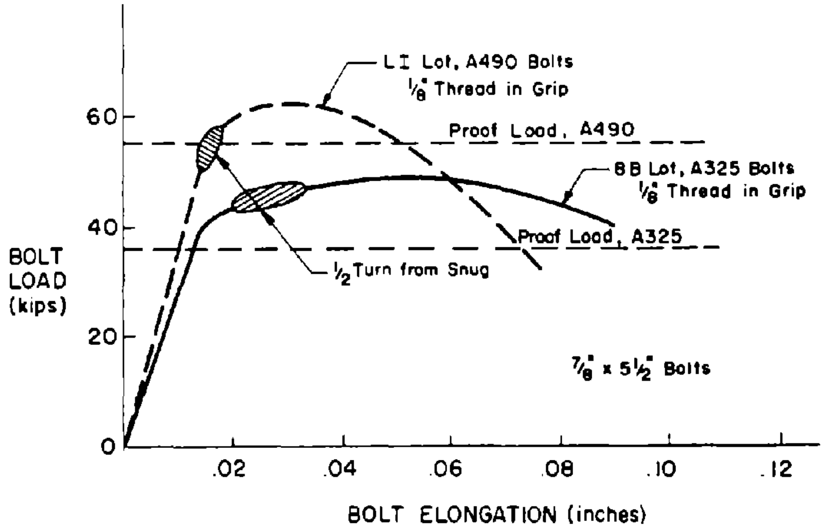


Figure 8. Comparison of A325 and A490 bolts calibrations.[29][32]

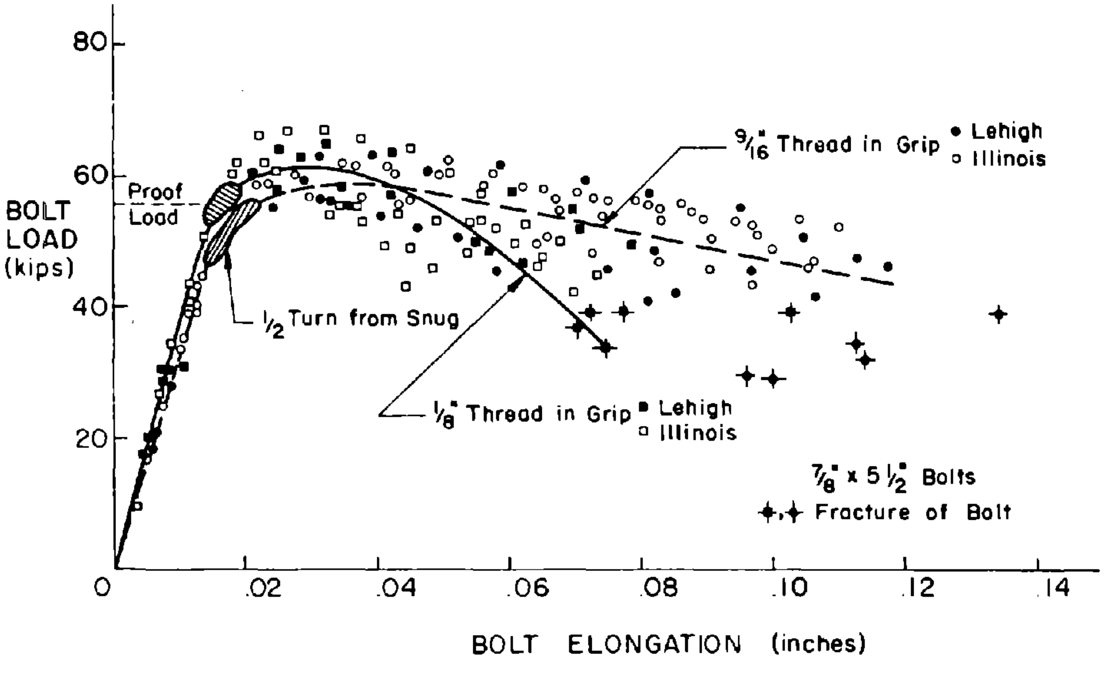


Figure 9. Effect of threads in the grip for A490 bolts.[32]

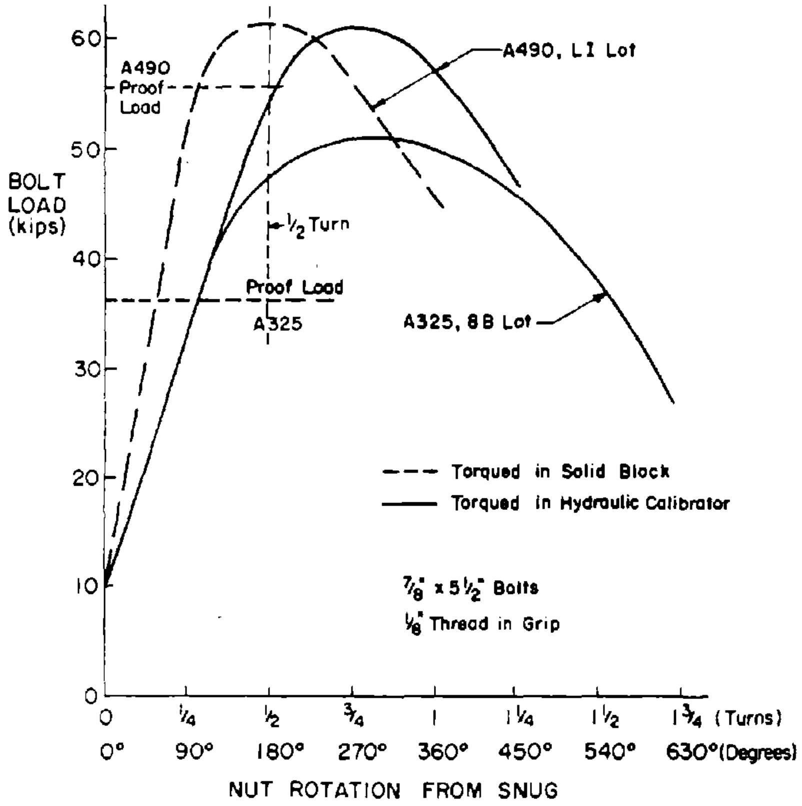


Figure 10. Comparison of solid block and hydraulic calibrator.[32]

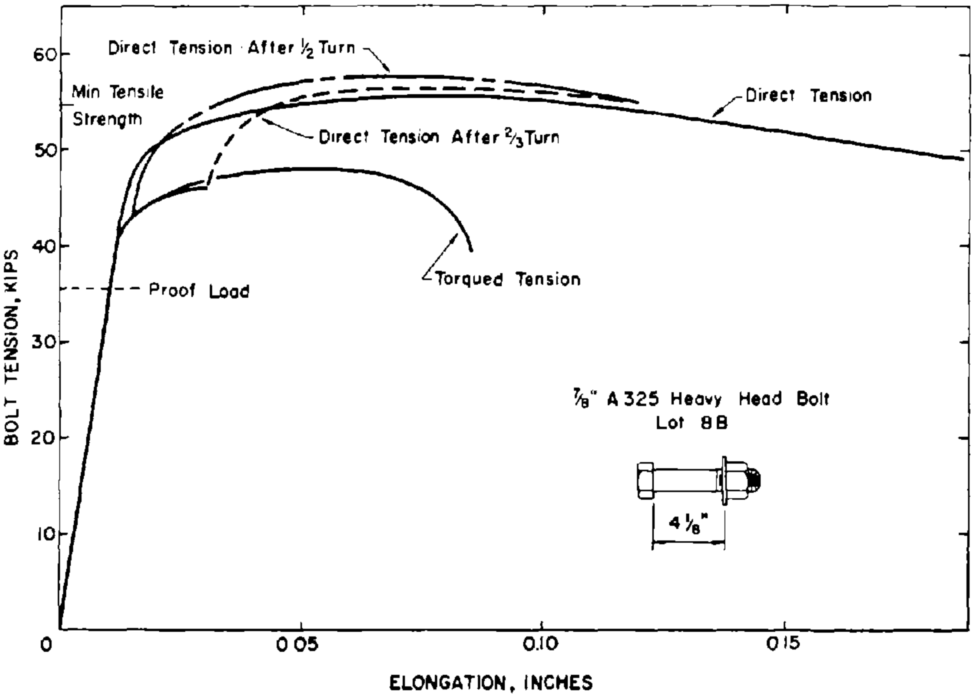


Figure 11. Torqued tension vs. direct tension.[29]

reached its maximum load at the installed rotation of one-half turn. This means that any over torquing or additional inspection using a torque wrench could decrease the force in the bolt.

The behavior of the A490 bolts in figure 10 also shows an undesirable characteristic of a very significant drop in tension before breaking. At only one full turn, the tension reduced to about 45 kips (200 kN) from its maximum of 62 kips (276 kN). This type of behavior, which is similar to stripping failure, must be avoided because it is difficult to detect in the field.

Various comparisons of Skidmore-Wilhelm calibrations to solid plate calibrations are published. In the elastic range, the Skidmore may indicate from 25 to 75 percent more turns to reach the minimum specified tension than are required in a solid steel assembly.[11] This amounts to 1/6 to 1/4 of a turn. Munse has recommended that the rotation at failure measured by a Skidmore be reduced by 60 degrees to get equivalent turns in a solid block.[21]

Torque. The presence of torsional stress has a very significant effect on the tension-turn response of a fastener assembly. A typical relationship is shown in figure 11 in which the torqued tension is 10 to 20 percent lower than the direct tension results. The actual reduction is very sensitive to lubrication and thread conditions; a good lubricant will keep torsional stresses low. Further discussion on the effect of lubricants will be given later.

A measured relationship between torque and tension in an A325 bolt-nut-washer assembly is shown in figure 12 for two different thread conditions, lubricated and cleaned. The relationships are reasonably linear up to near maximum load. A commonly used relationship

$$\text{Torque} = K \times P \times D \qquad (1)$$

is also shown where K is a dimensionless nut factor which depends on the material and the surface conditions of the threads, nut and washer, P is the

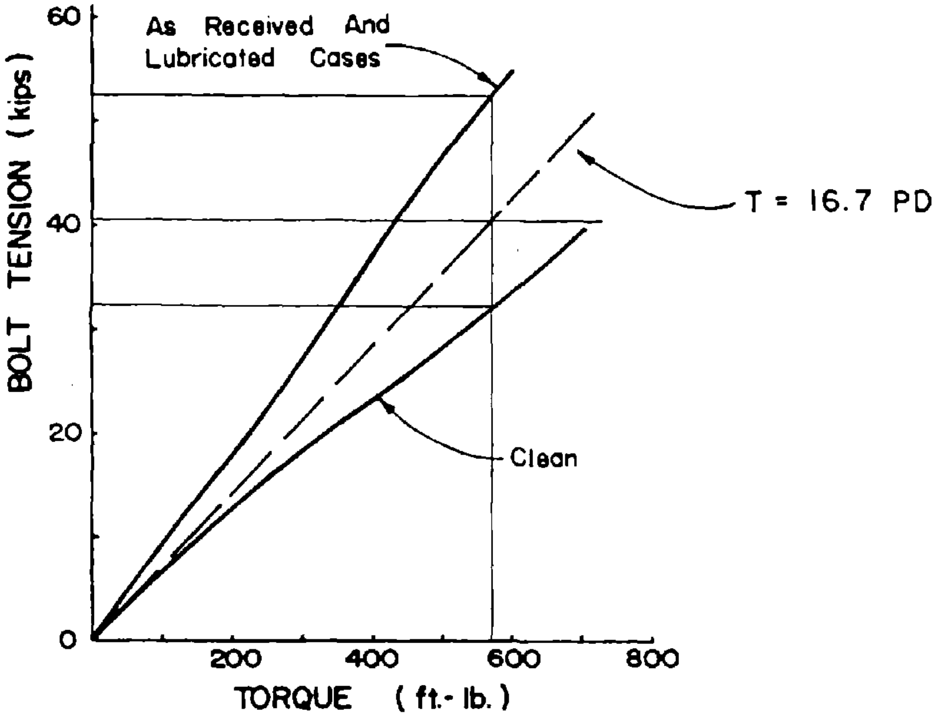


Figure 12. Typical tension-torque relationship.[12]

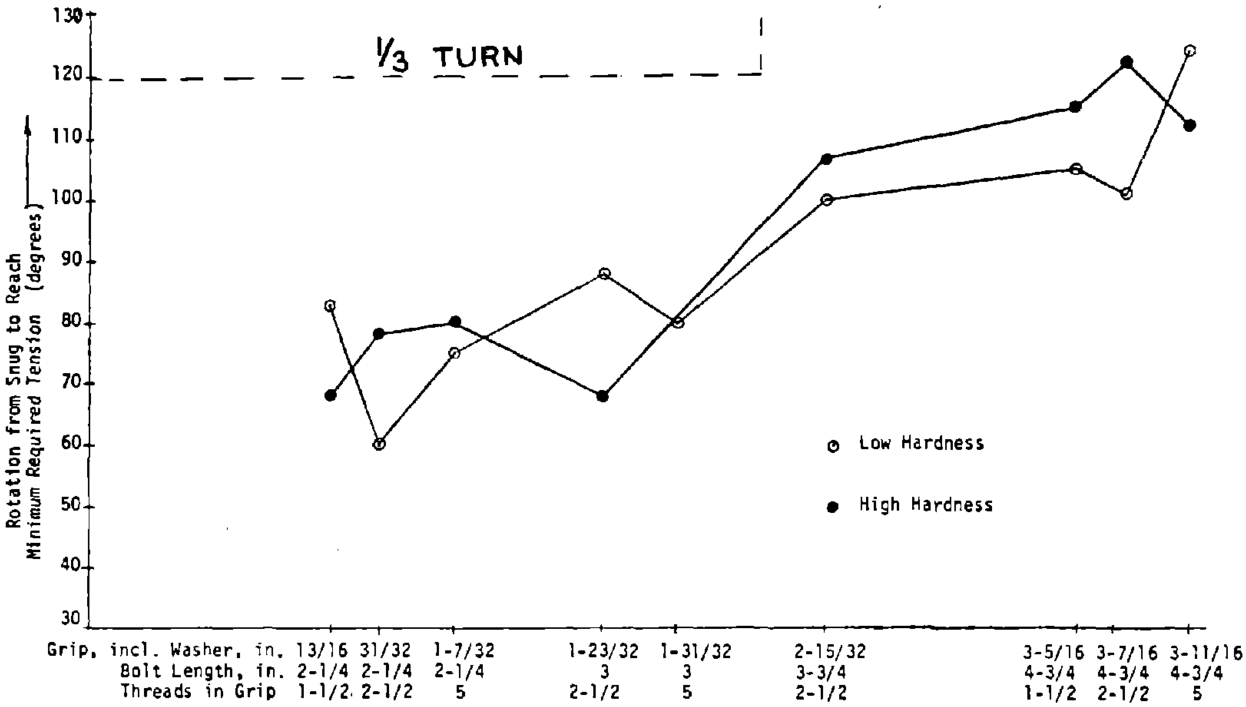


Figure 13. Effect of bolt length on nut rotation for required tension.[22]

desired bolt tension and D is the nominal diameter of the bolt.[11] In the first RCSC Specification, equation (1) was used to develop a table of required torques based on an average K for as received black bolts (lubricated with residual cutting oil) of 0.20. If units of P are in kips, D inches and torque in ft-lbs, equation (1) becomes

$$\text{Torque} = 16.7P\ D \qquad (2)$$

and is plotted in figure 12. Equation 2 is currently used in the Canadian Steel Specification as an inspection torque for bolts in bearing joints. The formula was removed from the RCSC Specification in 1960 because of wide variation of conditions in the field where K was found to vary between 0.18 and 0.29.[6] The actual tension-torque relationship (nut factor) must now be determined by an on-site calibration. The Japan Industrial Standard (JIS) refers to the same relationship between torque and tension but the K factor ranges between 0.11 and 0.19.[14] JIS states that the nuts and washers are to be treated with a chemical coating in order to reduce the frictional resistance. In figure 12, K = 0.15 for the lubricated conditions and K = 0.25 for the bolts cleaned with acetone. If equation 2 was used to install the lubricated bolts, the induced tension would be 53 kips (236 kN). If the bolts were not this strong, the bolts could break before the desired torque was reached. On the other hand, if the thread conditions approach the cleaned condition, the installation procedure would develop a tension of 33 kips (147 kN), 16 percent less than the minimum specified tension.

As a sample of the torque variations that can commonly occur during installation, Munse found that the torque necessary to achieve a bolt tension of 39 kips (174 kN) ranged from 350 to 790 ft-lbs. (474-1070 N-m) and averaged 535 ft-lb (725 N-m) for 87 tests on thirteen different lots of short grip A325 bolts. For this load equation 2 gives a torque requirement of 570 ft-lb. The laboratory torque results gave a variation of -38 percent to +39 percent compared to equation 2 with a mean of 1.06. For three different A490 lots, the range was from -32 to +3 percent. There was generally less than 5 percent scatter among the three replicates of each sample which suggests that a calibration test should provide a reliable installation torque for a given lot of bolts. Bolts from a single manufacturer, even though different lots, gave a consistent tension-torque relationship. Munse concluded that the manufacturer had a greater effect on the torque behavior than the length of the bolt or the number of threads in the grip.

The twist-off or spline-end bolt relies on a predictable linear relationship between torque and tension. This can only be achieved by careful manufacturing control of the bolt, nut and washer as a unit and the use of a reliable lubricant. It is important that the original assembly be left intact and that products of different manufacturers are not mixed.

Short Grip. Munse has reported tests on A325 and A490 bolts with grips less than 4 D.[21, 22] When bolts are short, the turns to failure will be smaller; therefore, there is more of a tendency to fail these bolts when installation is by the turn-of-nut method. For bolt lengths less than 4 D, the installation turn past snug is reduced to 1/3 turn of nut to accommodate this reduced deformation capacity. Figure 13 shows that the nut rotation for minimum specified tension is more a function of bolt length than of the number of threads in the grip. The required 1/3 turn level, shown dashed, should provide tensions well in excess of the minimum specified.

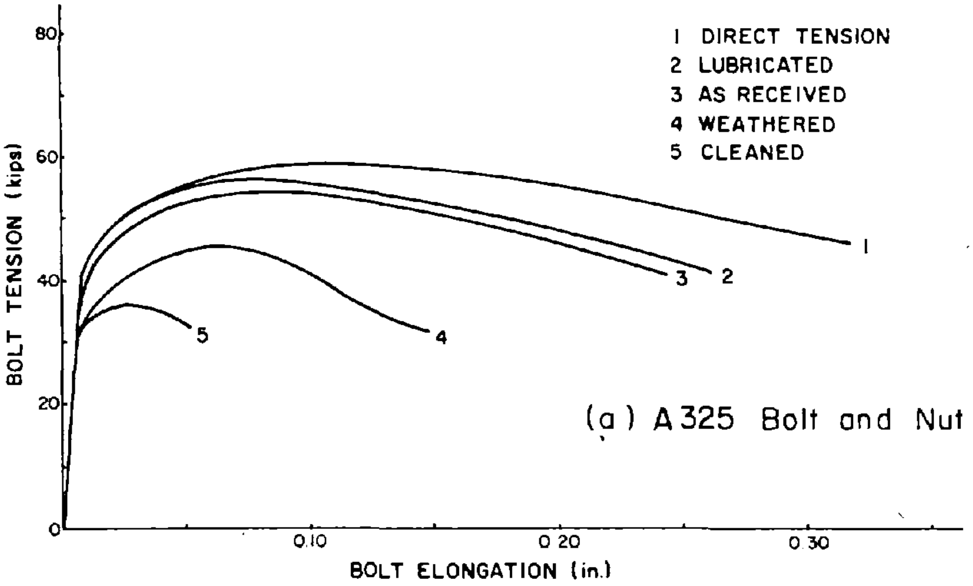
The turns-to-failure were very much a function of the bolt strength. The high hardness bolts that were 2-1/2 in long (57 mm) failed at an average rotation of 1.0 turn whereas the low hardness bolts reached 1.3 turns. For both of these lots, the maximum tension was reached at about 3/4 turn. This reduced deformation capacity also suggests that short grip bolts should probably not be reused unless they are installed by the calibrated wrench method.

Lubrication

When a nut is tightened the resistance encountered consists of three parts. First, energy or torque is required to force the nut up the inclined planes of the threads. Second, there is friction on the threads at the bolt-nut interface. Third, energy is required to overcome the friction between the nut, washer and gripped material. It has been found that 90 percent of the energy will go into overcoming the friction.[9] It is just as important to lubricate the nut face as it is to lubricate the threads.[11, 30] This can be accomplished by lubricating the entire nut. In one study with a lubricant called "No-Oxide" on the nut threads and surface, the torque was only 67 percent of that measured in the unlubricated state.[11] This reduction alone reduces the power requirements for installing high strength bolts and speeds up the tightening operation.

Lubrication also has a significant effect on the bolt calibration curve. A sample result shown in figure 14(a) is taken from Eaves' study on lubrication effects on high strength bolt behavior.[12] The lubricant used was an anti-seize copper base product, Fel-Pro C5-A. The as-received bolts and nuts had an oily coating which gave results similar to lubricated. Weathered bolts consisted of immersing the as-received bolts in water briefly, then dried outside. The process was repeated in 24 hours so the total weathering period lasted two days which was considered a possible reasonable exposure for unprotected bolts. Nuts were also weathered. The residual oil was obviously soluble in water because the strength and ductility of the weathered specimens were significantly reduced from the as-received. Bolts cleaned with acetone to remove all lubricant showed very poor performance. Failure occurred before the minimum specified bolt tension was reached. Installation torques were 60 percent higher for the clean threads. These results show the importance of proper on-site storage of bolts as required by the Bolt Spec.

Figure 14(b) which compares the calibration curves for an A490 bolt with different thread conditions, shows the same trend as the A325 bolt. The reduced ductility of the A490 bolt compared to the A325 bolt is apparent, even for good lubricated conditions.



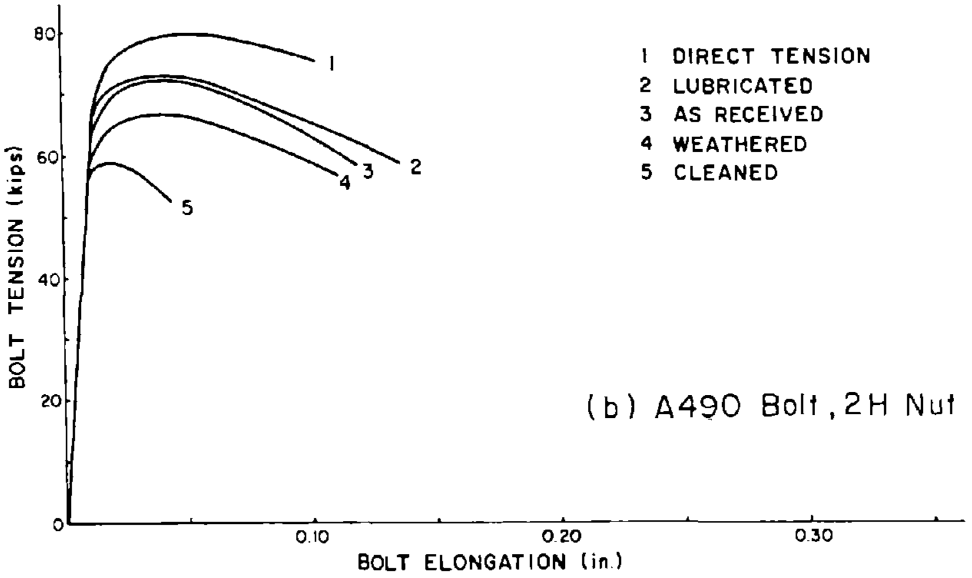


Figure 14. Bolt calibrations with different thread conditions.[12]

A variety of lubricants on high-strength bolts have been investigated. On black bolts, molybdenum disulfide, molecular graphite type, light oil and molycote, anti-seize and lubriplate 1200-2, Molycote Type G, beeswax and graphite grease, and beeswax have been used.[11, 9, 12, 21, 30] In all these studies with various lubricants there was no significant difference among the calibration curves although beeswax appeared to give slightly better results. The as-received bolts with light oil had about the same calibration curve as those with the lubricants. Specimens with no lubricant performed poorly compared to the lubricated nut condition. The beeswax and molybdenum disulfide did show significantly reduced applied torques compared to the other lubricants. Figure 15, which compares the calibration curves of an A490 bolt with different thread conditions, shows the same trend as the A325 bolt in figure 14. Lack of lubrication significantly reduces strength and ductility.

The effect of lubricants on installation of galvanized fasteners have been studied mainly at the University of Illinois under the direction of Munse and Birkemoe.[7, 21, 22, 24, 38] In galvanized fasteners, the torque has been found to be much higher and more variable than for black bolts. The problem is compounded for galvanized fasteners because the nuts must be overtapped to accommodate the zinc coating. Beeswax (BW), water soluble wax (SW), cetyl alcohol (CA), commercial solid wax (CW), petroleum base wax and molybdenum disulfide have been tested. The tension-torque relationship and the bolt calibrations for some of these lubricants are shown in figures 15 and 16. All the lubricants except the soluble wax gave bolt calibrations similar to black bolts. The soluble wax and as-received conditions gave tension-torque responses similar to those predicted by equation 2 but this did not guarantee good calibration performance, probably because the nuts were also overtapped thus requiring a superior lubricant.

Galvanized Bolts

In the 1960's research on galvanized fasteners and connections was undertaken at the Universities of Illinois, Washington and Toronto to investigate their suitability for use in bridges.[7, 21, 10, 18, 30] This

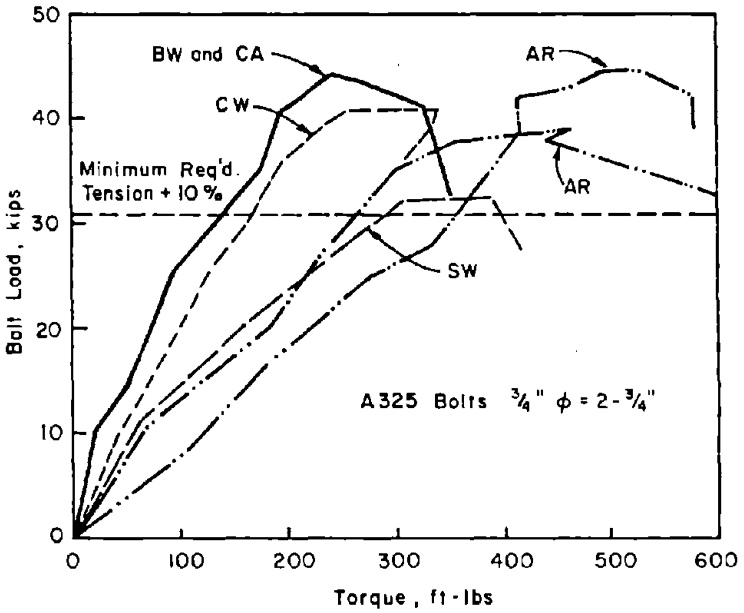


Figure 15. Tension vs. torque for lubricated hot-dip galvanized A325 bolts.[38]

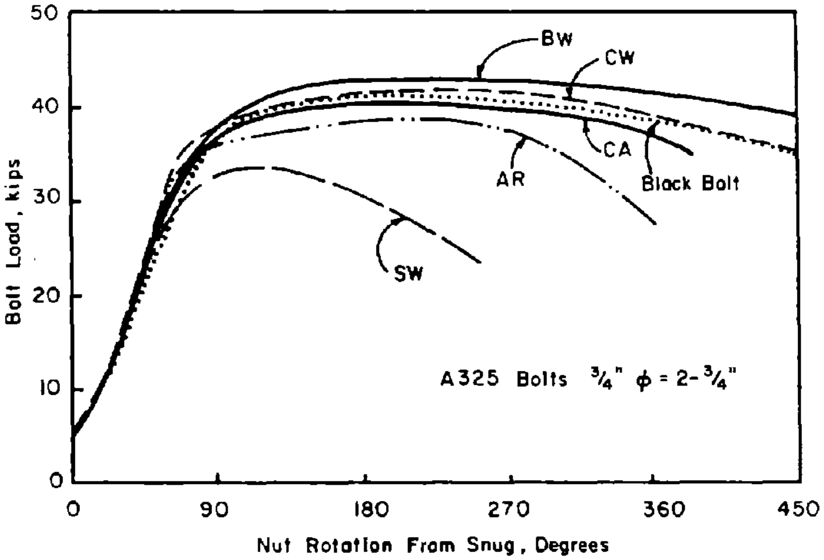


Figure 16. Effect of lubricants on hot-dip galvanized bolts.[38]

early work exposed a number of serious problems with the installation of galvanized fasteners, namely reduced strength and ductility, and high installation torques. A summary of this early research is given in reference 7. Briefly, it was desirable to install the bolts using the standard techniques. In the turn-of-nut method sufficient bolt ductility is required so there is a margin of safety between the required installed rotation and the number of turns to fail the bolt. The calibrated wrench method needs a consistent load-torque relationship within a lot of bolts. Both methods require low torques so that the torsional stresses do not fail the bolt and common installation wrenches can be used. The early studies showed that the torques were high and quite variable, the ductility was significantly less than black bolts and stripping failures were quite frequent. For example, the black bolts usually failed at 2.0 turns from snug whereas the galvanized bolts failed at slightly more than 1.0 turns. The amount of nut overtapping after hot dip galvanizing varied. The reported values were 0.015, 0.015 and 0.010-0.015 in (0.25 - 0.38 mm) for the Illinois, Washington and Toronto programs, respectively.

The special problems associated with galvanized fasteners were addressed in the ASTM A325 Specification issued in 1971 which permitted galvanized A325 bolts for the first time. Special provisions related to galvanized products are as follows:

- 2H (ASTM 194) and DH (ASTM 563) nuts were required. This high hardness nut requirement was used to offset the frequent nut stripping problems.
- Nuts were to be provided with an additional lubricant and the bolt and nut tested through one full turn of nut from snug in a solid plate without failure (rotation capacity test). This performance test was adopted to ensure that the assemblage had sufficient ductility to accommodate the turn-of-nut tightening method. A safety factor of two was used since one-half turn is required for installation. It is stated in the ASTM specification that this rotation test is a measure of the lubricant's efficiency.

- The galvanized bolts and nuts were required to be shipped in the same container. This provision was used to provide some assurance that the nut-bolt assembly, as tested under item (2) above, was sold and installed as a unit.
- A minimum 2 mil zinc thickness was specified along with a minimum nut over tap after hot dip galvanizing corresponding to 0.021 in (0.53 mm) for 7/8-in (22 mm) bolts.

The researchers at Illinois had recommended the rotation capacity test in item (2) above for all bolts, black and galvanized, since the lack of lubrication affects the strength and ductility of black bolts also, as shown earlier. But, the ASTM Committee adopted the test only for galvanized bolts. Since research was limited to nut overtaps less than 0.015 (0.38 mm), the generous overtap provided by this specification is surprising since stripping was a common problem.

Galvanized A490 bolts are not permitted because this early research indicated that they could only sustain 3/4 to 1 turn of the nut to failure which was less than that obtained by black bolts. Since hard nuts are already used with A490 bolts, no method to improve ductility is apparent. It was also found that galvanized A490 bolts were more susceptible to stress corrosion failure if the installed tensile stress in the bolt is high. [8]

Munse conducted additional research after 1971 on galvanized fasteners.[22, 24] The tests concentrated on short grip bolts and mechanically galvanized fasteners. Primarily 2H nuts with overtap up to 0.020 in (0.51 mm) were used. The results followed earlier patterns. Mechanically galvanized fasteners behaved similarly to hot dip galvanized bolts. When no lubricant was present, bolts broke at rotations less than 300 degrees. A significant number of stripping failures occurred when a commercial wax was used. As will be shown later, lubrication increases the likelihood of stripping. Thread stripping occurred even in some tension tests with overtaps of 0.010 in (0.25 mm) when only 1-1/2 threads were in the grip. Of the 36 tests on lubricated mechanically galvanized bolts, 23 failed by stripping. No nut or bolt dimension or properties are given in the report so the actual amount of thread engagement could not be determined. Only one of six fasteners stripped when the overtap was 0.010 in (0.25 mm) and 2H nuts were used. For the same conditions but with a 0.020 in (0.51 mm) over tap, eleven out of twelve stripped. Four out of six stripped when softer Grade 2B nuts [230 Brinnel] were used with 0.010 in (0.25 mm) overtap. This research indicates that the use of 2H nuts with the large overtap will not prevent stripping.

Stripping Failure

A bolt calibration curve that involves stripping is shown in figure 17. As the bolt or nut strips, tension reduces as the nut is turned. Unfortunately, the torque-tension relationship, as shown in figure 18, does not remain linear. Note that the torque stayed constant at about 800 ft-lb (1080 N-m) as the tension reduced from 60 kips (270 kN) to 30 kips (130 kN). The stripping type failure is undesirable since high torque is indicated when low tension is present with no external visual evidence that stripping has occurred. In the turn-of-nut method, if stripping occurs before the required number of turns, then additional rotation actually causes the tension to reduce, rather than increase. Stripping must be prevented in installed bolts in structures.

Literature Survey. Unfortunately, stripping has been a continuing problem. In probably the first major bridge to use high strength bolts, the Mackinac Bridge used over one million of the fasteners.[19] On this job significant nut stripping occurred. Care had to be taken so that the bolts were not overtorqued. A minimum and maximum torque was set up for this project which controlled the problem. In various laboratory tests, numerous stripping failures have occurred especially when A325 nuts were specified. Prior to 1978, no minimum hardness was required for the nuts. This was corrected in 1979 when ASTM removed nuts from the A325 specification, and Grade C nuts from the A563 specification were specified as the minimum strength. In reference 32, 4 out of 20 A490 fasteners stripped. The authors

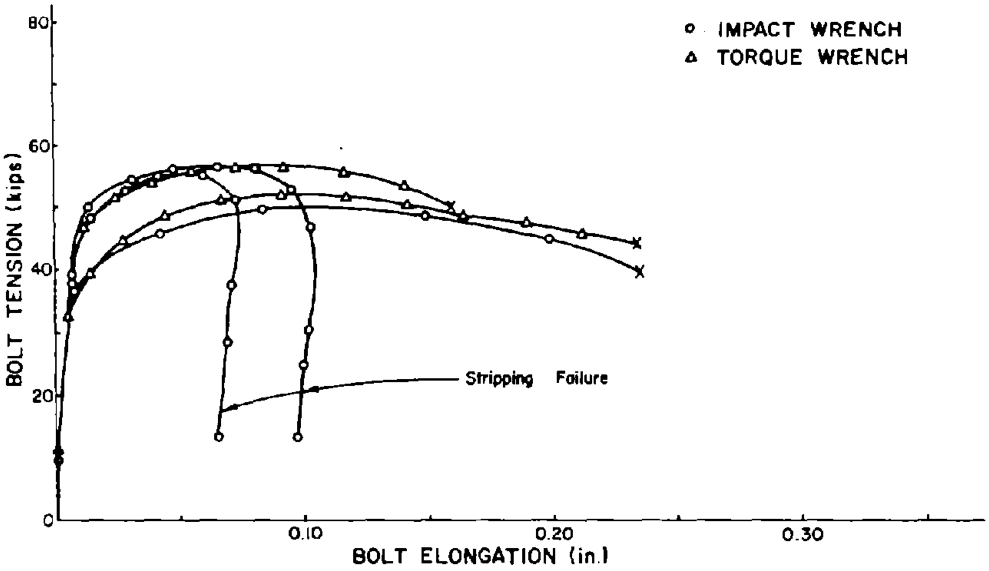


Figure 17. Stripping failure in an A325 fastener assembly.[12]

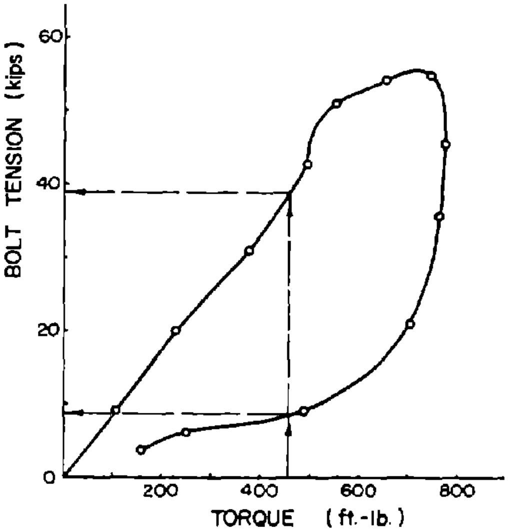


Figure 18. Torque-tension response for a stripping failure.[12]

attributed the stripping to the fact that the nut and bolt diameters were close to the extremes permitted for an Class 2A fit as required by the A490 Specification. Forty-four out of 51 tests in the short grip test program failed by stripping.[22] Most stripping occurred in the nuts but no nut properties were given. Much of the stripping occurred after very significant rotation occurred, in excess of 400 degrees for low hardness (ductile) bolts. For the high hardness bolts in the program stripping occurred near maximum load. As bolt tensile load increases the higher shear stresses on the thread increases the possibility of stripping. In a followup program, A490 bolts in short grips also stripped even though 2H nuts were used.[23] However, there were only 1-1/2 threads in the grip which means that any necking of the cross section reduces the thread engagement at the first few threads and also increases nut dialation which promotes stripping. In Eaves' research, stripping only occurred in black bolts when A325 nuts [$85R_b$] were used with A325 bolts.[12] As discussed earlier, almost all the studies with galvanized bolts had stripping failures. The overtapping reduces the thread interface, thus reducing the stripping strength.

Stripping failure is difficult to eliminate once it occurs. While lubrication improves bolt rotation capacity and strength, it decreases stripping resistance. So if lubrication is reduced, bolt performance will probably be unsatisfactory. Harder nuts can be used to replace the softer Grade C nuts if nut stripping is a problem. If bolt stripping occurs, nuts with a tighter fit might be a satisfactory solution. In all these cases the solution is costly and time consuming. The best solution is to minimize the possibility through changes in the appropriate specifications for the manufacture and installation of fasteners.

In the next section, current fastener specifications will be critiqued and a theory of stripping will be examined for possible improvement in current practice.

U.S. and Metric Fastener Specifications. The A325 and A490 bolt specifications have companion metric versions, A325M and A490M respectively.

The metric specifications are separate, with their own designation, date of issuance, and wording. Similarly, there are two versions of the nut specification, A563 and A563M. For 2H nuts, the U.S. and metric are covered under one document, A194/A194M-85. Except for the A194 specification, the "equivalent" U.S. and metric specifications for high strength nuts and bolts have some significant differences. Bolt, nut and thread dimensions, covered under ANSI B1 and B18 Standards listed in appendix A, are obviously different for U.S. and metric fasteners. However, the size of a 7/8 in (22.2 mm) diameter bolt is almost the same as the 22 mm (0.866 in) metric fastener, so they are permitted to be interchanged. A comparison of the dimensions of these two fasteners is given in table 1.

For black bolts the U.S. units Standard permits greater variations for both D and d, but a tighter fit (interface) is required, 0.0812 (U.S.) vs 0.0740 (Metric). The larger the interface, the tighter the fit. However, the metric specification requires harder nuts, a minimum of Rockwell 89B, and a larger nut height, H. As will be shown later, the greater nut strength more than offsets the looser fit so that metric fasteners will be less prone to stripping than fasteners manufactured to U.S. units. The minimum tensile strength of an M22x2.5, A325M bolt is 251 kN (56.4 kips), whereas the corresponding strength of an A325 -7/8 bolt is 55.45 kips (247 kN). The minimum specified tensile strength of the metric fastener is 2 percent greater than the U.S. bolt, even though the U.S. bolt is slightly larger.

The U.S. units Standard permits lower strength nuts than in A325M. Grade C and D nuts would not qualify for use with A325M bolts. The A325M specification was first approved in 1979. In an October 1, 1979 report to the RCSC, the subcommittee on metric fasteners reported:

> "Nuts have been designed so that if, during assembly, bolts are overtightened, the bolt will fracture rather than the nut strip. This corrects a situation which has plagued inch A325 bolts for several years."

Table 1. U.S. vs. metric A325 bolts and nut properties.

Size	D_s (in)		D (in)		d (in)		H (in)		F (in)		D - d Interface (in)		Bolt Hardness (Rockwell)		Nut Grade	Nut Hardness Rockwell	
	max	min	max	min	max	min	max	min	max	min	max	min	max	min		max	min
US 7/8 UNC	.895	.852	.8731 (.894)*	.8592	.7780 (.7990)	.7550 (.7760)	.885	.833	1.437	1.394	.1181 (.1181)	.0812 (.0602)	35C	24C	C D,2 DH,2H	38C 38C 38C	78B 84B 24C
Metric 22 x 2.5	.899	.833	.8645 (.8854)	.8513	.7773 (.7982)	.7596 (.7805)	.929	.878	1.417	1.378	.1049 (.1049)	.0740 (.0531)	34C	23C	8S 10S	38C 38C	89B 26C

*hot dipped or mechanically galvanized fastener tolerances shown in parenthesis

The power industry through its quality assurance program has noted that the experience with metric products is better than those with U.S. units with respect to stripping.[33] It is not clear why action has not been taken to update the U.S. units standard to minimize stripping.

Section 7.4 of ASTM A563-84 on galvanized nuts states:

> "7.4 Nuts to be used on bolts threaded with Class 2 A threads before hot-dip zinc coating, and then hot-dip zinc-coated in accordance with Specification A 153, Class C, shall be tapped oversize at least by the following minimum diametral amounts:
>
> | Diameter, in. | in.[A] |
> |---|---|
> | 7/16 and smaller | 0.016 |
> | Over 7/16 to 1 | 0.021 |
> | Over 1 | 0.031 |
>
> ---
>
> [A] Applies to both pitch and minor diameters, minimum and maximum limits."

The words "shall be tapped oversize at least by ..." appears to imply that there is no upper limit on overtapping and it cannot be less than 0.021 in (0.53 mm) for 7/8-in (22 mm) bolts. Discussions with bolt manufacturers and suppliers indicate that 0.021 in (0.53 mm) overtapping is treated as a minimum not a maximum. The intention of the ASTM Committee is that the limit is a maximum.[34] Large overtapping leads to stripping failures. The wording is different in the metric A563M-84 Specification so that the overtap is clearly a maximum, not a minimum limit as follows:

> "Such nuts shall be tapped over-size to have internal threads with maximum and minimum limits which exceed the maximum and minimum limits specified for metric coarse internal thread with Grade 6H tolerances by the following diametral allowances:

Nut Diameters	Diametral Allowance µm
M5	156
M6	200
M8	255
M10	310
M12	365
M14 and M16	420
M20 and M22	530
M24 and M27	640
M30	750
M36	860
M42	970
M48	1080
M56	1190
M64 to M100	1300"

<u>Model for Predicting Stripping</u>. Alexander developed a model to predict the strength of a bolt-nut assemblage.[2] The model is based on more than 2000 tests with 200 different conditions.[1] The results were also compared to other research and found to correlate within 92 percent with a 95 percent degree of confidence. Loading at various speeds and hand torquing did not alter observations. Three types of failure were considered: tensile failure of the bolt through the threaded area, bolt stripping and nut stripping. The model applies to fasteners loaded in pure tension and in torqued-tension as

when installing a high strength bolt in a slip critical connection. In torqued-tension, both the tensile strength and the stripping strength are reduced by the presence of shear stresses due to friction. However, the ratio of stripping/tension remains unchanged (within 5 percent).

The ultimate tensile load of the bolt, P_u, is

$$P_u = A_a F_b \tag{3}$$

where F_b is the bolt ultimate tensile stress and A_a is the tensile stress area given by

$$A_a = 0.7854 \left[D - \frac{0.9381}{n}\right]^2 \tag{4}$$

for the UNC thread profile shown in figure 1, where D = measured major diameter of the bolt threads and n = number of threads per inch. The tensile stress area is defined as the area calculated using the average of the pitch and minor diameters. Eq 4 accounts for the fact that the thread is not symmetric about the pitch line. The common tensile stress area used in design, A_s, and defined in ASTM A325, is

$$A_s = 0.7854 \left[D - \frac{0.9743}{n}\right]^2 \tag{5}$$

which assumes that the thread profile is symmetric about the pitch line. For a nominal 7/8 in (22 mm) bolt, the ratio $A_a/A_s = 1.029$. Both equations 2 and 3 will be used in subsequent sections, A_a when actual bolt material strength is required and A_s when checking compliance with ASTM Specifications.

The formulas for calculating the nut and bolt stripping loads for 7/8 in (22 mm) fasteners are given in Appendix B. In general terms the stripping strength is a function of the actual and relative bolt and nut strength, the height of the nut, the thread fit, coefficient of friction and the number of threads within the grip. Lubrication reduces the coefficient of friction which allows the nut to dilate more readily as the assemblage is tightened. The dilation reduces the depth of thread engagement, h_e, shown in figure 2 so the stripping resistance is decreased. The tests indicated that applying a phosphate and oil coating after heat treatment decreased the stripping strength by 12 percent compared to the as-received condition. The formulas in Appendix B assume a well-lubricated surface. No definitive coefficient of friction or lubrication characteristics are given to define a well-lubricated surface.

When only a few threads are within the grip, the stripping strength is reduced because some bolt necking occurs inside the nut, thus reducing h_e. In addition, the confinement provided by the unthreaded shank and the thread friction within the nut restricts the necking which increases the bolt tensile strength by 10-20 percent so stripping is more likely.[2] This is why the rotation capacity test required for galvanized fasteners [ASTM-A325] and the tension test for full size bolts [ASTM-F606] require a certain number of threads within the grip. For bolts installed in structures, no such minimum thread requirement exists. The Alexander model does not include the effect of thread length within the grip.

The effects of the principal variables of nut strength (F_n), bolt strength (F_b), major diameter of the bolt threads (D), minor diameter of the nut (d), and nut height (H), on the Alexander stripping resistance are illustrated in figures 19-21. The equations in appendix B were used to develop these figures. In these figures, the bolt and nut stripping loads, B_s, and N_s, respectively, are nondimensionalized by the bolt tensile breaking load, P_u. When the ratio B_s/P_u is greater than 1.0, then bolt fracture would be expected before bolt stripping. Figure 19 shows both the nut stripping and bolt stripping strengths as a function of nut strength. As the nut strength increases, the nut stripping strength increases almost linearly. The nut strength also has a favorable, but much smaller, effect on bolt stripping. In figure 19 a bolt strength of 156 ksi (1076 MPa) was used, which is the maximum

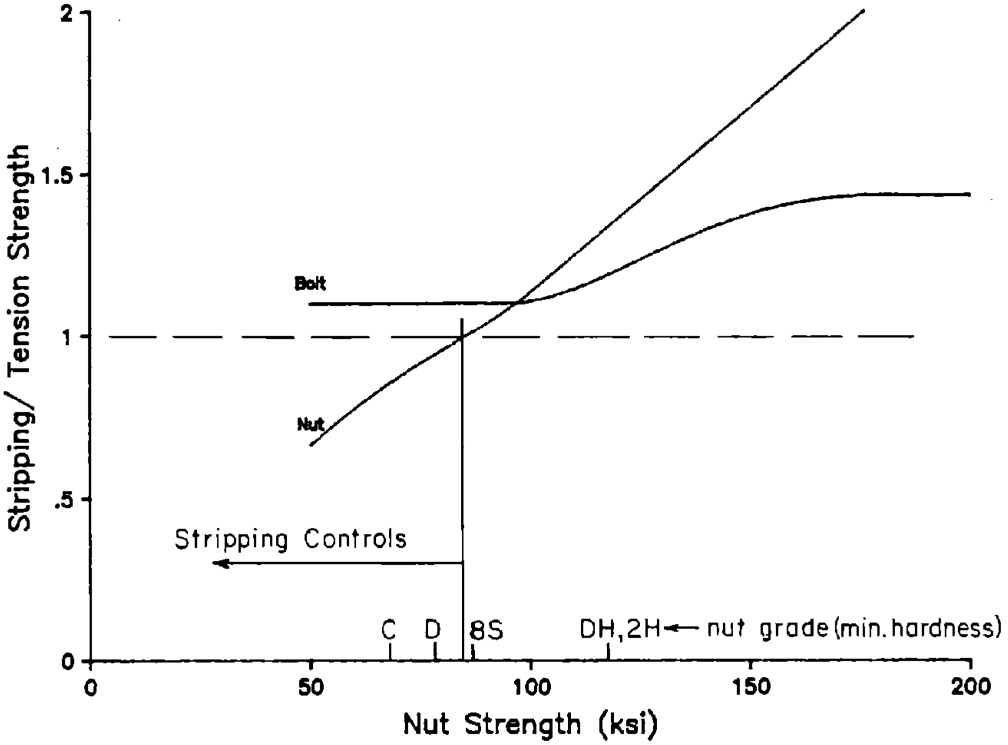


Figure 19. Effect of nut strength on bolt and nut stripping.

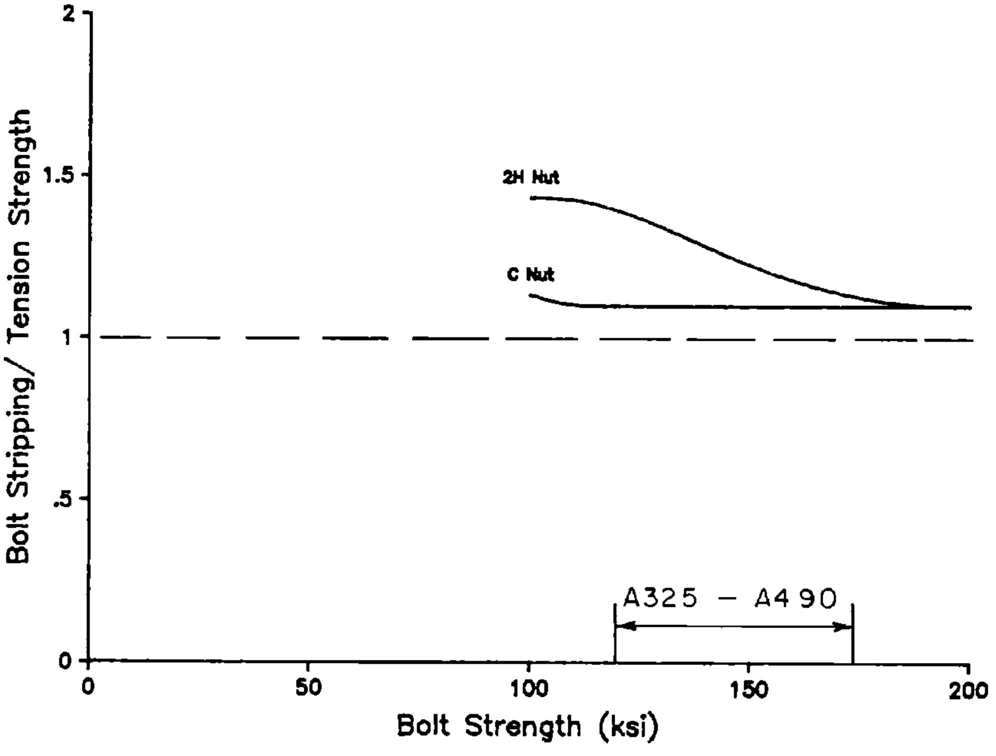


Figure 20. Effect of bolt strength on bolt stripping.

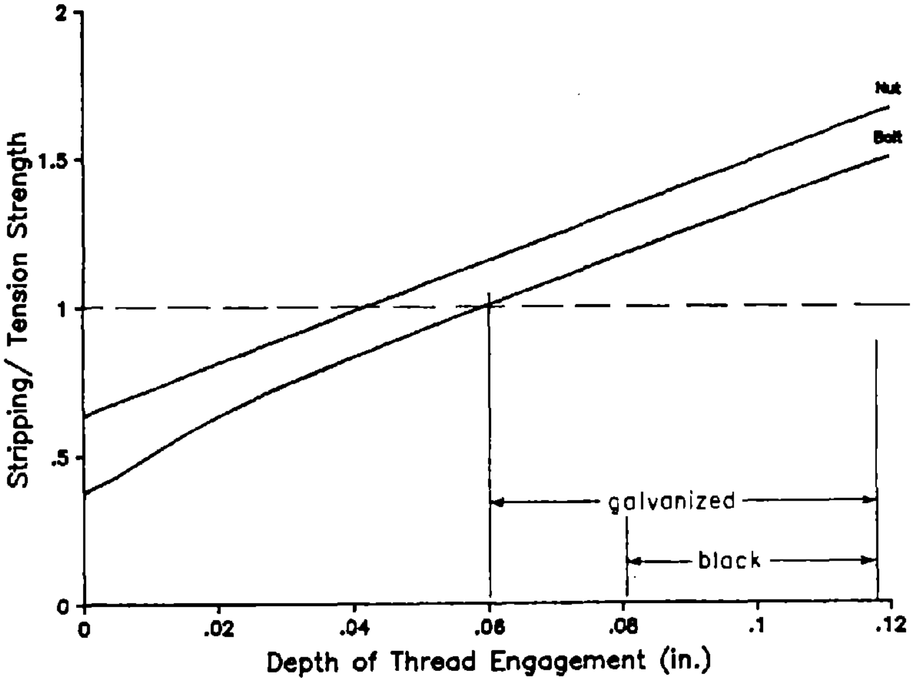


Figure 21. Effect of fit on stripping.

approximate tensile strength based on the maximum hardness of an ASTM A325 bolt. The higher the bolt strength, the more likely nut stripping will occur before bolt fracture. Other geometric variables for black bolts were kept at the specified maximum or minimum limits for a 2A fit as per ANSI B1.1 and for bolt and nut dimensions in ANSI B18.2, whichever gave the smallest ratio of stripping/tensile strength. If the nut strength is less than 87 ksi (600 MPa), then stripping will be likely if the bolt strength is at the maximum. Minimum hardness Grade C and D nuts permitted by ASTM-563 for use with A325 bolts fall in this category. Nut stripping should not occur if 2H or DH nuts are used. Surprisingly, the A563 Metric specification places a minimum hardness limit of 89 R_B on the 8S nuts for use with A325(M) bolts which is much higher than the 78 R_B required for Grade C nuts in the U.S. units A563 specification. According to the Alexander model, there should be no stripping in metric A325 bolt-nut assemblages, and experience on nuclear plants show that metric products do have less stripping problems.[33] Metric 22 mm (0.87 in) bolts can be used in place of 7/8-in diameter bolts.

Figure 20 indicates that bolt stripping should not occur in high strength black bolts with a 2A fit. The relationship between bolt stripping and bolt fracture remains relatively constant through a wide range of bolt strengths. With a high hardness nut, bolt stripping/bolt tensile decreases slightly as bolt strength increases, but the ratio does not fall below 1.0.

The Alexander model was developed from experiments on uncoated (black) bolts from normal production runs, so the measured depth of thread engagement of most samples represented by $h_e = D-d$ would fall within the range expected for a 2A fit. For a 7/8-in (22 mm) fastener, the range defined by $(D_{max}-d_{min})$ and $(D_{min}-d_{max})$ is shown in figure 21. For black bolts the range is from 0.081 in (loose fit) to 0.118 in (tight fit) (2.05 mm to 3.00 mm). For discussion purposes the stripping loads shown in figure 21 were calculated for full range of h_e, starting from zero (the nut will just slip along the bolt). The nut strength used was a minimum strength 2H or DH (119 ksi, 820 MPa) and the bolt strength was a maximum strength A325 (156 ksi, 1076 MPa), although the bolt curve would not change very much if a lower strength bolt was used. The model incorrectly predicts significant stripping strength at $h_e = 0$, which indicates that the results will be unconservative for tolerances outside the 2A fit for black bolts used in the regression analysis. For galvanized fasteners, ASTM A563 extends the range of h_e by 0.021 in (0.53 mm), and, as discussed earler, the wording of this specification is commonly interpreted to mean that the overtapping must be greater than 0.021 in (0.53 mm), resulting in a smaller h_e for galvanized fasteners than indicated in the figure. Although the results show that bolt stripping would be just marginal for galvanized fasteners, since $h_e = 0.06$ in (1.52 mm), more frequent stripping may occur in practice because the model is inaccurate at loose fit, and smaller h_e than intended by the specification can be possible. Through much of the practical range of fit, the stripping strength is a reasonably linear function of h_e. A change of 0.01 in (0.25 mm) in the fit will alter the stripping load 8 to 10 percent.

The nut height is almost directly related to stripping strength. The nut dimensional tolerances are quite small so this factor should not alter stripping loads by more than 3 percent if the nuts are within specifications. However, it is interesting that the minimum height of a 22 mm (0.87 in) heavy hex nut (ANSI B18.2), 0.878 in (22.3 mm), is 5 percent higher than the U.S. units 7/8-in (22 mm) nut, 0.833 in (21.2 mm).

Alexander's model has had a significant influence on the development of the A325 metric bolt.[35] Specified nut dimensions, minimum nut strength, and maximum bolt strength give ratios of stripping strength/tensile strength greater than one. This work, however, has had little effect on the U.S. units A325 specification. Black A325 bolts with C or D Grade minimum strength nuts may exhibit stripping problems. 2H and DH nuts are required for use with A490 bolts which are not permitted to be galvanized. For this combination of nut strength, bolt strength and fit, no stripping is predicted for A490 bolts. However, stripping may occur if there are only a few threads in the grip.

When testing replicates, only some of the sample may show stripping if the ratio of stripping/tension ratio is close to 1.0. Under ideal conditions some stripping may occur with ratios up to 1.05. When comparing the model prediction to test results on galvanized fasteners, bolt and nut dimensions should be measured with the zinc removed since the zinc will not contribute to the thread strength.

CHAPTER 3. EXPERIMENTAL METHODS AND FASTENER PROPERTIES

Thirteen different bolt and nut assemblies were tested; three A325 black (B), four A490 black (B), four A325 hot dip galvanized (HG) and two A325 mechanically galvanized (MG). All lots were purchased on the open market. Three addition sets of nuts were also obtained. Orders were always placed using the ASTM bolt designation and the request for "matching nuts" to determine what the vendors would supply. In a purchase order fasteners were requested to be from one lot and of domestic manufacture. Certifications were requested on all fasteners. The various lots were necessary in order to obtain a sufficiently large sample with a wide range of tolerances. Various commercial lubricants were also tested to establish their suitablity and efficiency. It was also hoped that the large number of lots would contain some fasteners with stripping problems, so special taps would not have to be purchased to study stripping which was a principal phenomenon to be investigated.

Two general categories of tests were conducted, one to measure the material and dimensional characteristics of the bolts, nuts and washers and a second to study the performance of the bolt-nut-washer assembly. Tension tests and hardness measurements were performed on all bolts and only hardness tests were conducted on the nuts. All dimensions were measured by micrometers. The measured properties of the bolts and nuts are given in table 2 with symbols defined in figures 1 and 2. Three different types of tests were conducted on the bolt-nut assembly: tension tests, turn tests in a layer of solid plates, and torque-tension-turn tests. The turn test is required for galvanized fasteners only by ASTM A325.

Dimensions

The values shown in table 2 for the black A325 and A490 fastener lots are averages calculated from measurements on four samples taken randomly from the lot. Variations in the diameters within a lot were approximately ±0.003 in (0.076 mm). The thread length L was measured from the first full thread to

Table 2. Measured properties of bolts and nuts.

	BOLTS								NUTS								
Lot No. (1)	Type (2)	D_g (in) (3)	D (in) (4)	L (in) (5)	Z_b (mils) (6)	R_c (7)	F_U (ksi) (8)	Mill F_u (ksi) (9)	Type (10)	d_w (in) (11)	d_n (in) (12)	H (in) (13)	H_b (in) (14)	F (in) (15)	R_c (16)	Mill R_c (17)	Z_n (mils) (18)
BLACK (B)																	
A	7/8 A325 X 3	.870	.864	1.53		29	144	144	A563	.780	.780	.869	0.00	1.408	32	33	
H	7/8 A325 X 5	.872	.867	1.62		25	132	131	A563	.761	.773	.843	0.23	1.416	33	33	
T	7/8 A325 X 4	.868	.866			27	137	NA	A563	.776	.775	.864	0.00	1.402	97B	NA	
B	7/8 A490 X 3	.870	.864	1.56		37	175	157	2H*	.778	.781	.858	0.27	1.397	28/33	32	
G	7/8 A490 X 5	.872	.866	1.56		34	165	168	2H	.762	.771	.848	0.25	1.419	29	28	
L	7/8 A490 X 5	.871	.871	1.38		34	169	NA	2H	.776	.777	.871	0.00	1.418	33	NA	
J	1 A490 X 4-1/2	.997	.995	1.81		36	169	NA	2H	.896	.900	.982	0.25	1.582	34	NA	
P									2H	.778	.769	.882	0.28	1.408	33	NA	
HOT-DIP GALVANIZED (HG)																	
C	7/8 A325 X 3	.875	.873	1.53	2.7	28	142	149	2H	.801	.811	.862	0.28	1.403	26	28	3.2
w/o ZINC		.863	.865							.812	.815	.838		1.391			
E	7/8 A325 X 5	.873	.866	1.56	2.3	26	151	134	2H	.789	.787	.861	0.00	1.408	27	28	3.5
w/o ZINC		.865	.858							.798	.798	.855		1.401			
I	7/8 A325 X 5	.881	.875	1.56	3.6	25	133	131	2H	.797	.793	.878	0.25	1.415	31	28	3.5
w/o ZINC		.868	.861							.797	.789	.870		1.412			
K	7/8 A325 X 5	.875	.873	1.41	2.9	30	155	NA	2H	.795	.797	.873	0.20	1.417	32	NA	3.5
w/o ZINC		.863	.863							.802	.805	.867		1.407			
MECHANICALLY GALVANIZED (MG)																	
D	7/8 A325 X 5	.873	.862	1.62	0.6	26	137	129	2H	.808	.807	.875	0.00	1.393	31	32	1.0
w/o ZINC		.868	.857							.812	.812	.866		1.390			
F	7/8 A325 X 5	.872	.866	1.44	1.5	31	146	138[1]	2H	.786	.795	.857	0.25	1.417	28	NA	3.8
w/o ZINC		.865	.864							.792	.799	.852		1.408			
Q									2H	.797	.769	.889	0.25	1.410	32	NA	2.5
w/o ZINC										.798	.774	.884		1.405			
R									2H	.775	.764	.865	0.25	1.412	33	NA	2.4
w/o ZINC										.779	.768	.857		1.406			
ASTM-ANSI	7/8 max	.895	.873	1.50	2.0					.778	.778	.885		1.437			
(black)	7/8 min	.852	.859							.755	.755	.833		1.394			

NM = not measured; NA = not available; *A194 - Class 2H; [1] estimated from hardness

NOTE: 1 mil = 0.001 in., 1 in. = 25.4 mm, 1 ksi = 6.895 MPa the end of the bolt. The inside diameter of nut (minor diameter) was measured on the washer side, d_w, and the identification side d_n. In some cases, there was a significant difference between d_w and d_n, indicating a bell-mouthed profile as shown in figure 3. In these cases, depth of the bell-mouthed portion, H_b, was measured. Usually H_b was about two threads deep. The minor nut diameter at the bell-mouthed end was measured at the first thread from the end of the nut.

For comparison the ASTM-ANSI dimensional tolerances for uncoated (black) 7/8-in (22 mm) bolts are shown at the bottom of the table. These limits should not be compared to Lot J, which is a 1-in (25 mm) fastener. For galvanized fasteners, the D, d_w and d_n limiting values can be increased by 0.021 in (0.533 mm) as per ASTM A325.

For the galvanized fasteners the dimensions were measured with the zinc removed on one sample from each lot. The bolts were dipped in hydrochloric acid for about five minutes to remove all zinc. It was established that no dimensional change occurred in uncoated bolts when immersed in the acid solution for this length of time. Measurements on the galvanized bolts were taken before and after the acid bath so that dimensions shown are for just one sample. The bolt dimensions are within the required limits except for Lots D and E which are slightly low for the zinc removed conditions. The measurements are satisfactory if experimental error (±0.003 in, 0.0762 mm) is considered. The black nut dimensions are all satisfactory. Except for the Q and R nuts, all the galvanized nuts are near or exceed the upper limit of d = 0.778 + 0.021 = 0.799 in (20.3 mm) intended by the ASTM committee. As explained earlier, ASTM 563 is not clear, since an overtap of "at least 0.021 in." (0.533 mm) is required. Lot D, which was mechanically galvanized, has a nut diameter substantially over 0.799-in (20.3 mm) limit. The same is true for Lot C, which is hot dipped galvanized. The nut dimensions measured on the four lots of hot dipped galvanized nuts, which represent three different manufacturers, indicate that the ASTM oversize limit is being treated as a minimum, not a maximum. Because of the unclear wording, all the nuts would be considered satisfactory. Otherwise, Lots C and D would be rejected.

Zinc Thickness

The thickness of the zinc coating was measured by a nondestructive magnetic microcomputer thickness gauge, Dermitron D-3000, with an accuracy of ±0.01 mils (±0.00025 mm). Two bolts and nuts were selected from each lot. Measurements were taken at ten locations on the shaft of a bolt and a mean and standard deviation determined. The average mean from the two samples is shown in col. 6 of table 2. In a similar fashion, 10 readings were taken on the exterior faces of the nuts and the results are given in col. 18.

All the hot dipped galvanized bolts and nuts exceeded the zinc coating thickness requirement of 2.1 mils in ASTM A153. The coating thickness on the mechanically galvanized bolts was less than the 2.0 mil requirement in ASTM B 695 for the required Class 50 thickness. For the thirty-two pieces tested, the average standard deviation was 0.4 mils, which indicates that the variation in thickness over the surface is generally not more than about 1 mil. The zinc thickness on the mechanically galvanized nuts satisfied the ASTM Specifications. The variation in zinc thickness measured on a particular bolt was about the same for hot dip and mechanically galvanized processes.

Hardness Tests

The bolt hardness was measured at six locations at a section through the threaded portion of the bolt. The section was made at a distance of one bolt diameter from the end of the bolt. This location, which is used in the case of arbitration in ASTM F606, was chosen because hardness reading at the ends, wrench flats or unthreaded shanks showed a wide scatter in a previous study.[12]

The hardness readings on the nut were taken on one of the flat sides that was machined down a few thousandths of an inch following ASTM F606 recommendations. Nuts specified to ASTM A 194, the Specification for 2H nuts, refers to hardness testing as per ASTM 370 which requires hardness readings on the top or bottom face of the nut. Five readings were taken on a straight line between the washer face and the identification face of the nut.

The average hardness data are given in table 2. All values are Rockwell C except for Lot T, in which Rockwell B was required because of low hardness. For all bolt lots except C and K, the six hardness readings used to calculate the average were very consistent with a standard deviation of about 1 R_C. For Lots C and K the standard deviation was 3 and 4 R_C, respectively. The standard deviation of the five hardness readings for a sample was less than 1 R_C for all nut lots. All nuts and bolts satisfied the minimum hardness requirements. For A325 and A490 bolts, the hardness must be in the ranges 24-35 and 33-38, respectively, on the Rockwell C scale. Nuts for black A325 bolts can have hardness with a range 78 R_B to 38 R_C. For use with galvanized A325 and black A490 bolts, 2H nuts must have a hardness within 24-38 R_C. Two average values for hardness are given for the Lot B nuts because variations in the nut markings indicated there must be two different lots within this group. The mill certification hardness, when available, is also given in the table. The correlation between the laboratory and mill hardness values is good.

Direct Tension Test

The tension tests were conducted in a fixture attached to the loading heads of a universal test machine. A photo of the fixture is shown elsewhere.[16] A bolt was installed with a nut and tensile load applied until failure occurred. The maximum load was recorded as the tensile capacity.

The ASTM tensile capacity test, usually conducted by the bolt manufacturer for certification, is detailed in ASTM A325 and F606 (see Appendix A). By this procedure the maximum load from the test machine is divided by the nominal tensile stress area given by equation 3 and is listed as F_u in table 2. The mill certification is given in Column (9) of table 2 for comparison. ASTM A325 requires a minimum strength of 120 ksi (827MPa). No maximum tensile strength is given but the specified hardness range 24-35 R_C can be converted to an approximate tensile strength range of 119-156 ksi (821-

1076 MPa) was using conversion tables in ASTM A370. A minimum and maximum strength, 150-170 ksi (1034-1172 MPa), is given in ASTM A490.

In most instances our results are close to those shown on the certification. Some of the comparisons are quite different which may be due to the following reasons. For A325 and A490 bolts up through 1-in (25 mm) diameter, a 10 degree wedge is required under the bolt head in a tension test to check the ductility of the junction of the head and body. A wedge was not used in our tests so that a basic tensile strength could be obtained. Thus, Lot B with a F_u = 175 ksi (1207 MPa) should not be considered out-of-specification which calls for a maximum F_u = 170 ksi (1172 MPa). Also, some certifications may not be valid for the bolts delivered. For example, no lot numbers were given on the Lot E certification, so their validity cannot be traced.

The purpose of the tension tests of the full size bolts was to determine the tensile strengths of the bolt material and the bolt-nut assembly. The F_u shown in table 2 are the averages of three tests for basic bolt material strength. In most instances the bolts were tested with the corresponding nuts delivered by the supplier. However, if stripping occurred rather than bolt fracture, the bolts were tested with nuts from other lots until a reliable bolt tensile strength could be established. The results of all tension tests are presented in detail in the next chapter. Different combinations of bolt and nut lots were used to determine the effect of thread engagement length on the tensile capacity of the bolt-nut assemblage.

Shear Strength

Because shear strength data of individual bolts are limited, simple shear tests were conducted on bolts from one lot in each of the four bolt groups tested, namely, black A325, A490, hot dipped galvanized, and mechanically galvanized. The average results of three bolts from Lots H, K, G, and F are given in table 3. The test fixture is shown elsewhere[16, 36]. The bolt

Table 3. Single shear tests.

Bolt Type (1)	Bolt Lot (2)	Ten. Str. (ksi) (3)	Average Shear Load Threads (kips) (4)	No Thrds (kips) (5)	Shear / Tension (6)	Threads / No Thrds (7)
A325-Black	H	132	38.2	47.3	0.595	0.809
A325-HG	K	155	46.8	54.6	0.585	0.857
A325-MG	F	138	43.8	52.5	0.598	0.834
A490	G	165	48.1	57.8	0.583	0.832
				Avg	0.591	0.830

1 ksi = 6.895 MPa, 1 kip = 4.445 kN

Table 4. Rotation capacity test - galvanized fasteners.

Bolt Lot	Type(1) Galv.	No. Tests	No. Passed	Type of Failure
C	HG	2	0	Stripped
E	HG	3	0	Torque-tension
I	HG	3	1	Torque-tension
K	HG	3	1	Stripped
D	MG	*	*	
F	MG	3	3	None

(1) HG = Hot Dip Galv., MG = Mechanical Galv.

*None tested in the as-received condition.

lengths permitted two shear tests on each bolt, one through the threads and one in the gross (shank) area. There was no tension in the bolt.

The ratio of the ultimate shear stress, column 5 divided by the gross area of the bolt, and the ultimate tensile stress, column 3, is given in column 6. The average of 0.591 for the four lots is very close to the 0.6 used in Alexander's model and the mean of 0.62 reported by Fisher and Struik[2,13]. This correlation indicates that there was little friction in the system and that the results are reliable.

The ratio of the shear load for the thread and no thread areas is given in column 7. The average is 0.83 which is considerably higher than the current recommendation of 0.7.[27] The results herein are consistent with the 0.815 reported in reference 16 for three different lots of A325 black bolts using the same fixture and with the 15 percent reduction mentioned in reference 4. The four lots in table 3 represent three different manufacturers; the test scatter within each sample of three bolts was less than 5 percent.

The current design reduction factor of 0.7 is based on the assumption that the effective shear area in the threaded zone is the root area.[37] The tests used to develop this recommendation were double shear connections with the bolts fully tightened by the turn-of-nut method. Special bolts were used with varying thread lengths. It is difficult to explain the results because of the friction and varying bolt tension plus the fact that different connections had to be compared rather than shear planes on the same bolt, as reported in table 3. Geometric considerations (a cut taken perpendicular to the bolt axis) and visual observations show that the shear area is greater than the root area. The shear area should also be larger than the tensile stress area used for tensile loading. The ratio of the tensile stress area to the gross area for a 7/8-in (22 mm) bolt of 0.769 is less than the threaded area reduction factor of 0.830 in table 3, which seems reasonable. The current reduction factor for threads in the shear plane of 0.7 appears to be too conservative and a value of 0.80-0.85 would be more realistic.

Rotation Capacity Test

For galvanized A325 fasteners, the manufacturer is required to test the bolt-nut assemblage to determine the efficiency of the lubricant as described earlier. For the 3-in (76 mm) bolts, the nut must be rotated 300 degrees past snug without failure. For bolts between 4 and 8 in (100 to 200 mm) long, the rotation requirement is increased to 360 degrees. A number of flat 5/8-in (16 mm) plates were used to built up to the desired grip so that 3 to 5 full threads would remain in the grip. The assembly was brought to the snug position using a spud wrench. Measurements on a Skidmore-Wilhelm bolt calibrator indicated that the snugging operation induced a tension of approximately 7 kips (31 kN). The rotation was applied using a large torque wrench. Some preliminary trials showed there was no significant difference in the results if the nut was turned by an impact wrench.

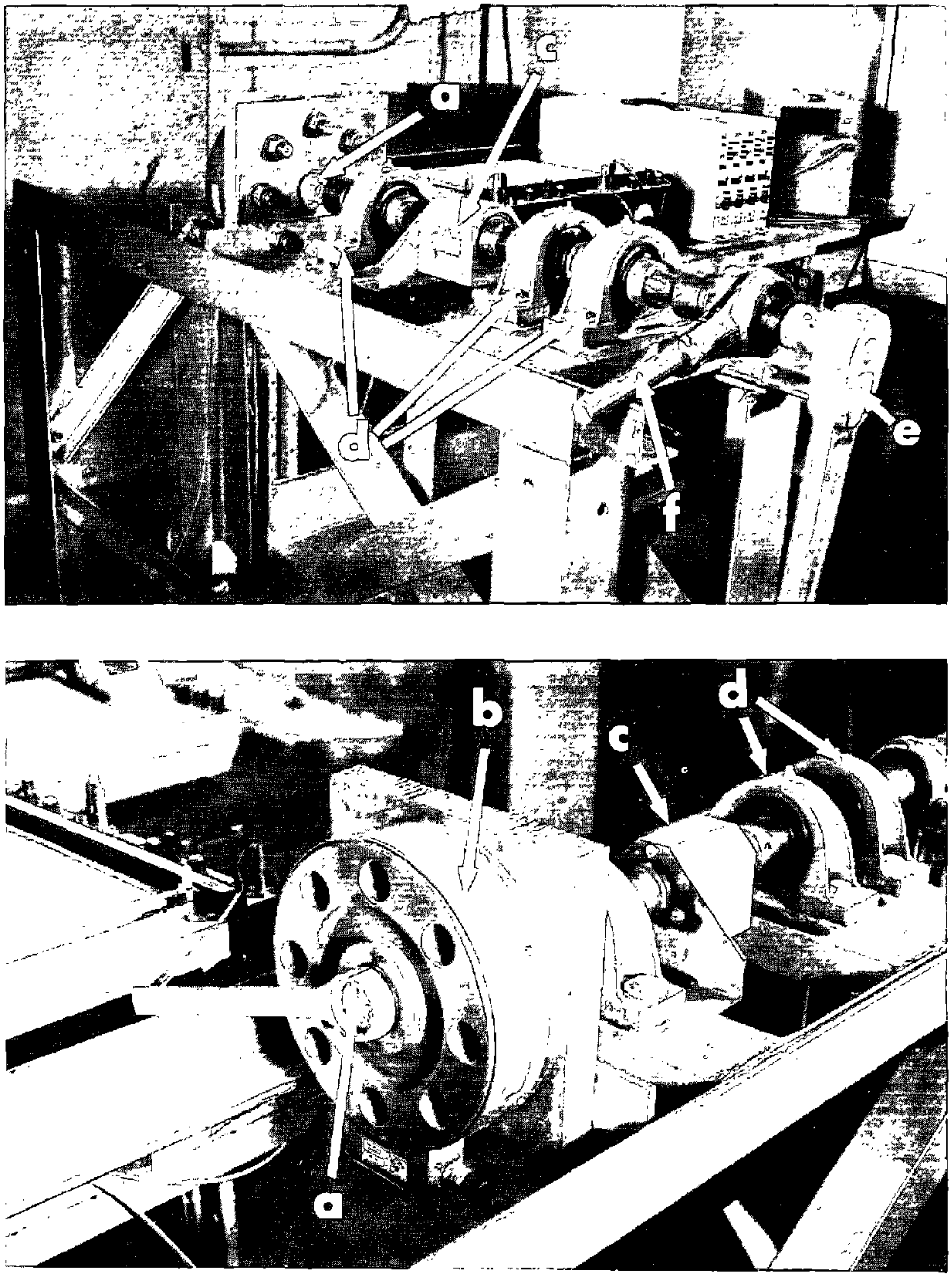
The bolts were installed in the as-received, cleaned or lubricated condition. After the required turns were achieved, the nut and bolt were disassembled and examined for failure as defined by ASTM A325, Section 6.5. Bolts from all lots were subjected to the rotation-capacity test, not just the galvanized fasteners. The results of the turn tests for the galvanized fasteners in the as-received condition are given in table 4. No manufacturer's rotation-capacity results were given in the test certifications for the galvanized bolts, so no comparison can be made with mill reports. D bolts were not tested in the as-received condition because of a limited supply, but other rotation-capacity tests in flat plates are reported in chapter 4. Except for Lot F, all galvanized bolts failed the ASTM rotation-capacity test in flat plates.

It is apparent from the large number of failures that the rotation-capacity test required by ASTM is not routinely conducted by the bolt suppliers. A visit by the authors to a bolt manufacturing facility verified this opinion. This particular manufacturer conducted the test in a Skidmore-Wilhelm calibrator, not solid plates. As shown later, and by others, the Skidmore gage is more flexible than solid plates and is not an acceptable substitute for solid plates.[11,32] The technician also exhibited little experience with the test requirements.

Torque-Tension Test

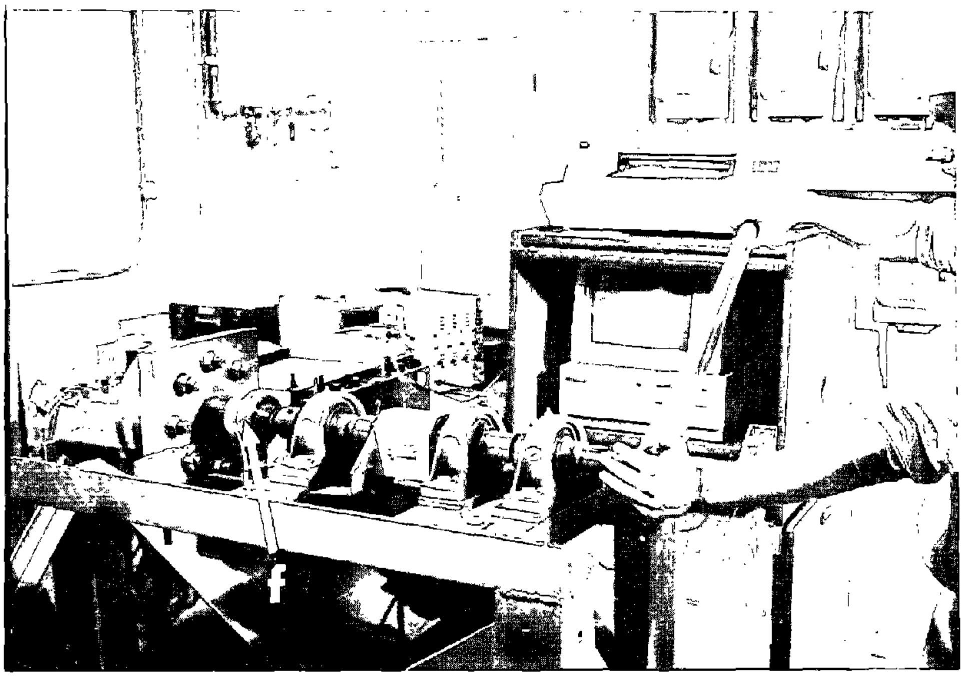
The principal experimental effort in this research program was devoted to the measurement of the torque-tension-turns relationship for the bolt-nut-washer assembly with various lubricants and tolerances. A test setup was developed which automated the data acquisition, as shown in figure 22. The bolt, nut, and washer were installed into a flat solid 100 kip (445 kN) load cell. For bolt lengths smaller than 4.5 in (114 mm), a Skidmore-Wilhelm bolt calibrator was substituted for the load cell. A threaded insert in the load cell permitted a length adjustment so that three to five threads would be within the grip. A wrench held the bolt head from rotating during the tightening process. A long socket extension was used which went from the installation wrench (e) to a torque multiplier (f) for ease in hand tightening, through two roller bearings (d) to a 1200 ft-lb (1600 N-m) torque load cell and turn counter (c) with electronic output, and to a final bearing for alignment. The components of the long extension were attached to a sliding platform to engage the socket with the nut. Early in the program it was discovered that the torque load cell, which had a capacity of two and one-half times the normal installation torque for a 7/8-in (22 mm) A325 bolt, limited the ability to take some of the bolt-nut assemblages to failure because of high torques. This was overcome by rearranging the location of the torque multiplier from that shown in figure 22 to a position between the nut and the torque load cell, as shown in figure 23. This latter arrangement required the calibration of the torque multiplier for input into the data acquisition system.

The scanning capabilities of the data acquisition system enabled the simultaneous recording of tension, torque, and turns using a microcomputer. After each test was completed, significant data points were stored as shown in a typical tension-turns response given in figure 24. The test was terminated when the bolt broke or the measured tension fell to less than 90 percent of



a	test bolt
b	tension load cell
c	torque & rotation
d	bearings
e	installation wrench
f	torque multiplier

Figure 22. Tension-torque-turns test setup.



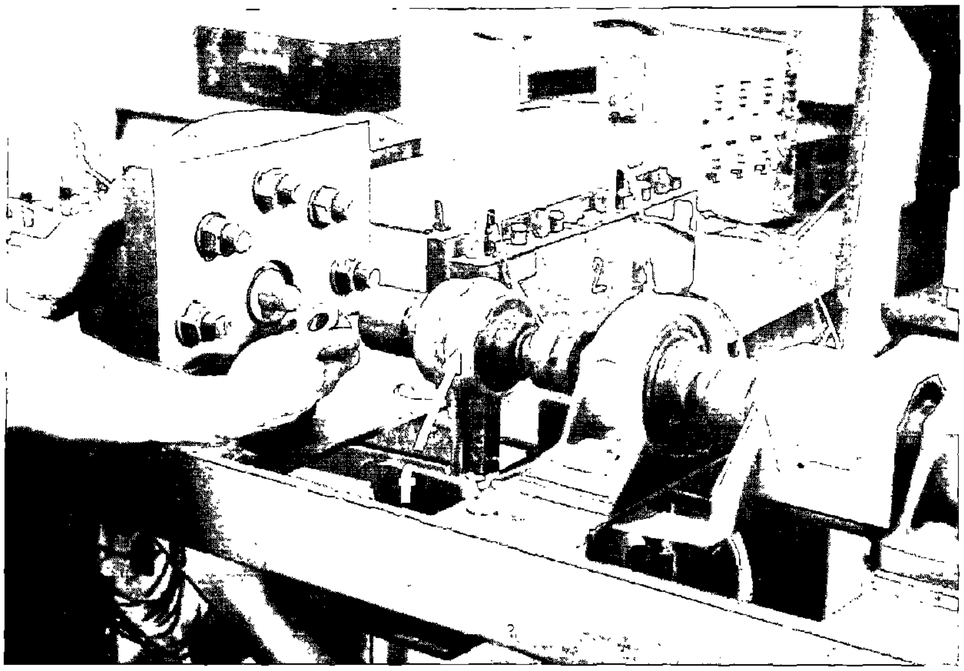


Figure 23. Rearrangement of the torque multiplier.

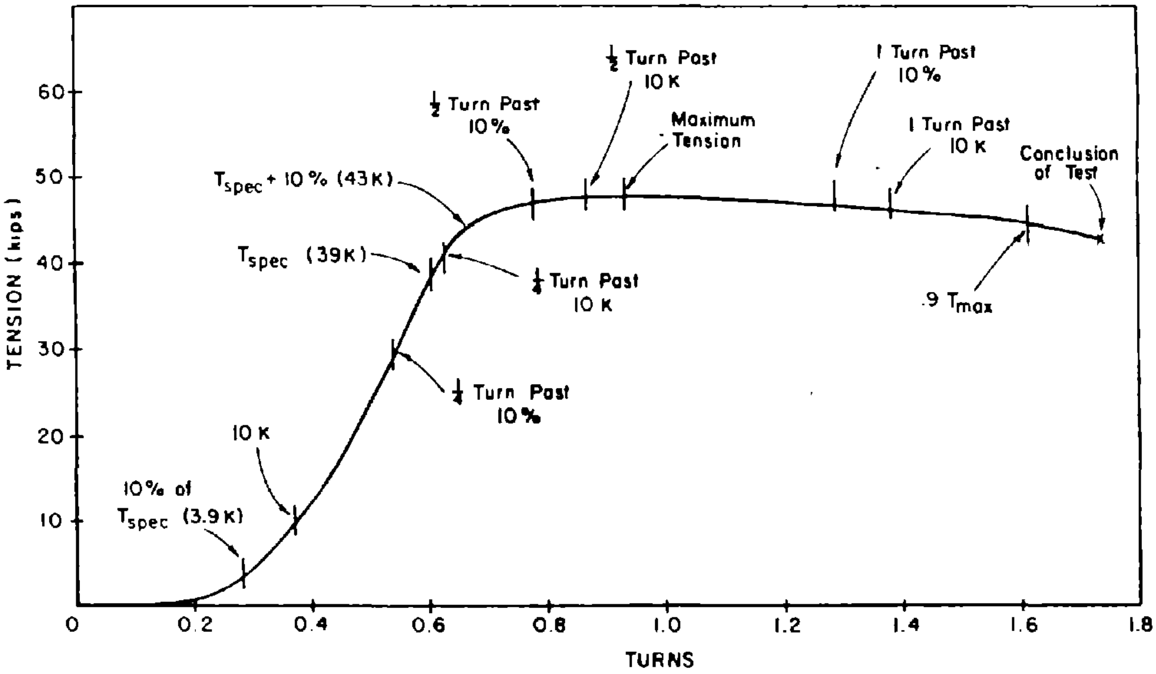


Figure 24. Typical tension-turn data.

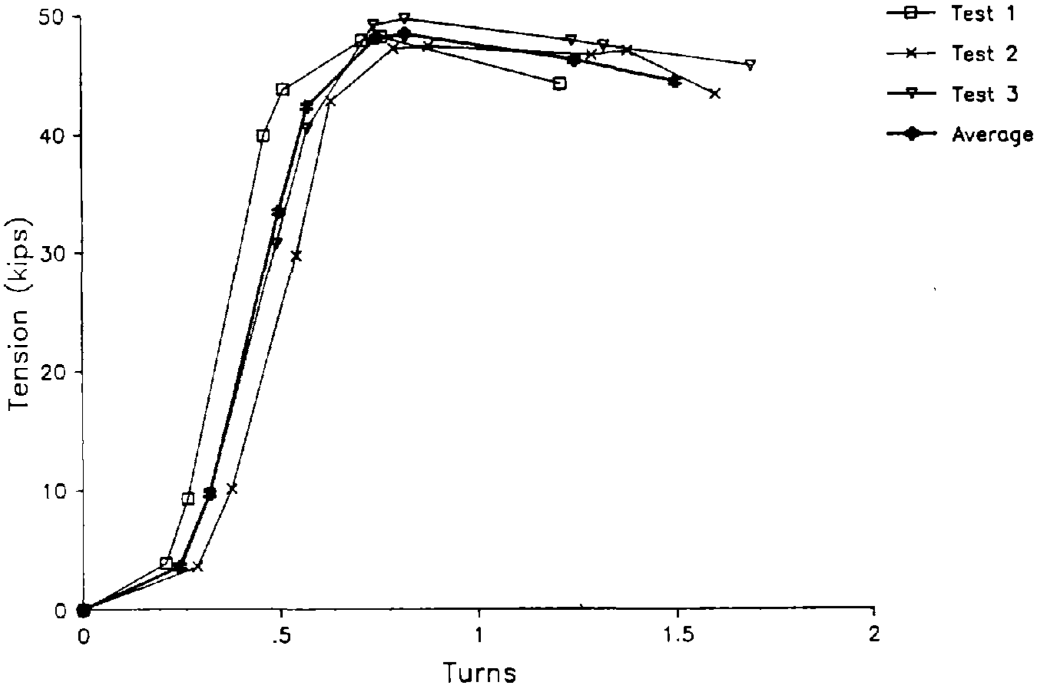


Figure 25. Tension-turn relationship for three replicates.

T_{max}. This termination point was used to avoid serious stripping which would make it difficult to remove the bolt from the setup. The data for three replicates was then combined to produce an average response, as shown in figure 25. Usually the response among replicates was very uniform. In the subsequent chapters, the response curves given are the average of three replicates unless otherwise noted. Sometimes, this averaging process results in some discontinuities which are not indicative of actual behavior.

Stiffness of Test Setup

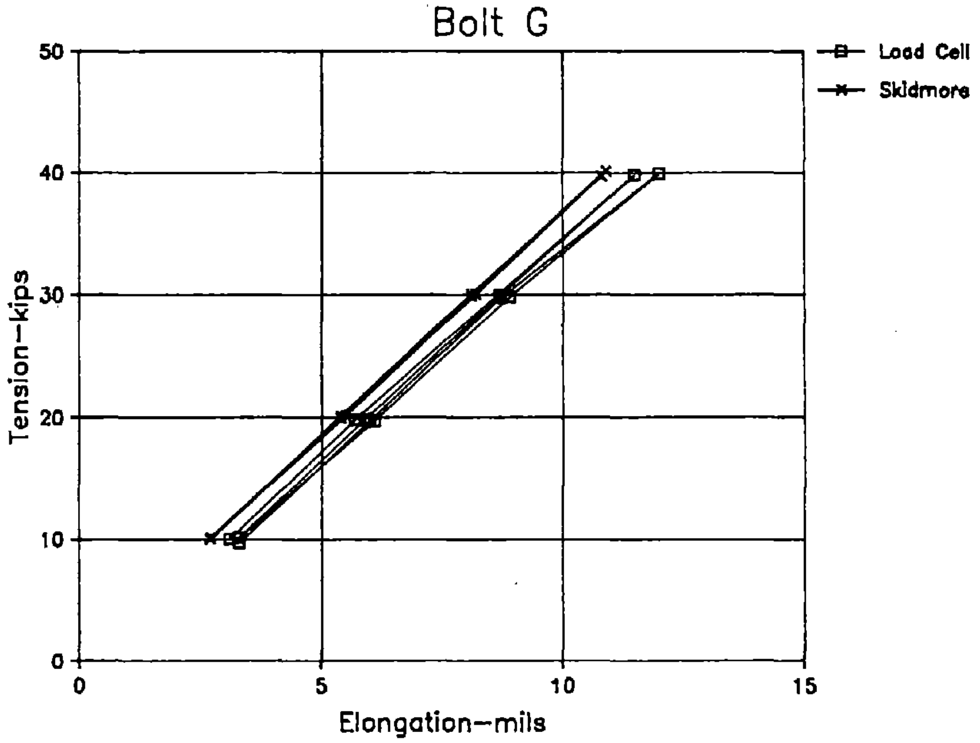
The ASTM A325 specification requires the turn test for galvanized bolts be performed using solid steel plates and/or washers in the grip of the bolt. The two test setups which were used to measure the tension, turns, and torque during the bolt tightening had bolt tension measuring equipment in the grip of the bolt. Short bolts were tested using a standard Skidmore-Wilhelm Model M hydraulic bolt tension indicator. The longer bolts were tested using a flat shear-type load cell to measure the bolt tension. In order to determine the stiffness of these devices relative to the plates and washers used in the ASTM test, a series of experiments was performed. The tests determined the relationship between the rotation of the nut to the elongation of the bolt. This was done for both test setups to compare with the behavior when a solid plate is used in the grip.

A bolt and nut from Lots B and L were used to measure the stiffness of the test setups relative to solid steel plates. Bolts from two different lots were used to determine the significance of bolt type upon the results. A490 bolts were used to provide the largest range for the tests. The nut rotation was measured using the digital turn sensing equipment in the torque load cell. The elongation of the bolts was measured using a Raymond Engineering ultrasonic bolt elongation gage. The rotation was measured to an accuracy of ± 2 degrees, and the elongation to ±0.0002 in (0.005 mm). The bolt tension was monitored in the test setups to ensure that the bolts were not tensioned into the inelastic range. The same bolts were used in each test. Washers were used to increase the grip of the Skidmore gage. All tests were performed with a grip of 3-3/4 in ±1/16 in (95 ± 1.6 mm). Each bolt was cycled at least twice during each test to determine the reproducibility of the results.

The tension versus elongation of the bolts tested with the Skidmore and with the load cell are shown in figure 26. The results are seen to be independent of the type of load-indicating device. The tension versus the nut rotation shown in figure 27 for the same tests do not match each other. More turns are required in the Skidmore than in the load cell to produce the same tension. This is not unexpected since previous researchers have noted that the hydraulic load cell used in the Skidmore is more compliant, less stiff, than a solid plate.[11, 32] The difference in the tension-turn results between the two test setups is due to the difference in stiffness of the two bolt tension measuring devices. More turns are required using the Skidmore than the load cell to produce the same elongation due to the lower stiffness of the Skidmore.

After the tests were performed using the two bolt tension measuring devices, the same bolts were inserted into solid plates. The bolts were then tightened to a quarter of a turn from the snug position and turned back to the snug rotation. The bolt elongation was measured at the snug position and at one-quarter turn.

The results were analyzed to determine the relationship between turns and bolt elongation. Figure 28 shows a plot of the average value of the nut rotation divided by the bolt elongation for the two test setups and the solid plate. The load cell and the solid plate have approximately the same stiffness. The Skidmore has about half the stiffness. Consequently, a bolt tested in the elastic range in the Skidmore will require approximately twice the amount of nut rotation from the snug position to reach a certain tension as the same bolt in a compacted steel joint in the structure. The load cell was found to have slightly more stiffness than the solid plates. Consequently, the turns to minimum tension and turns to failure recorded using the load cell to measure bolt tension are indicative of bolt behavior in an



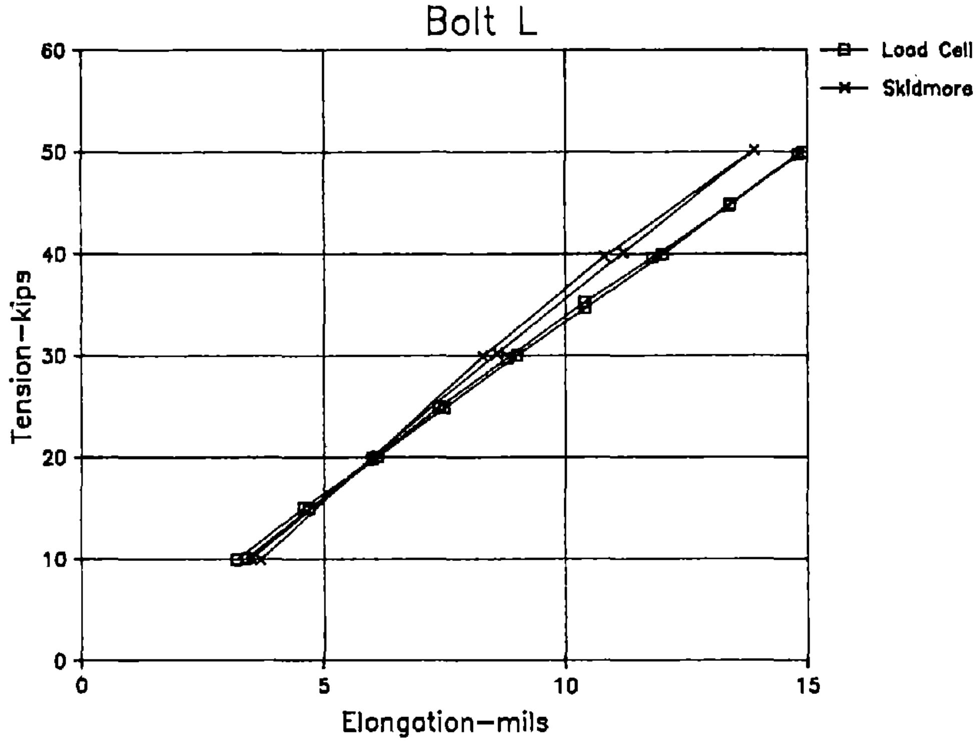


Figure 26. Bolt tension - elongation in elastic range.

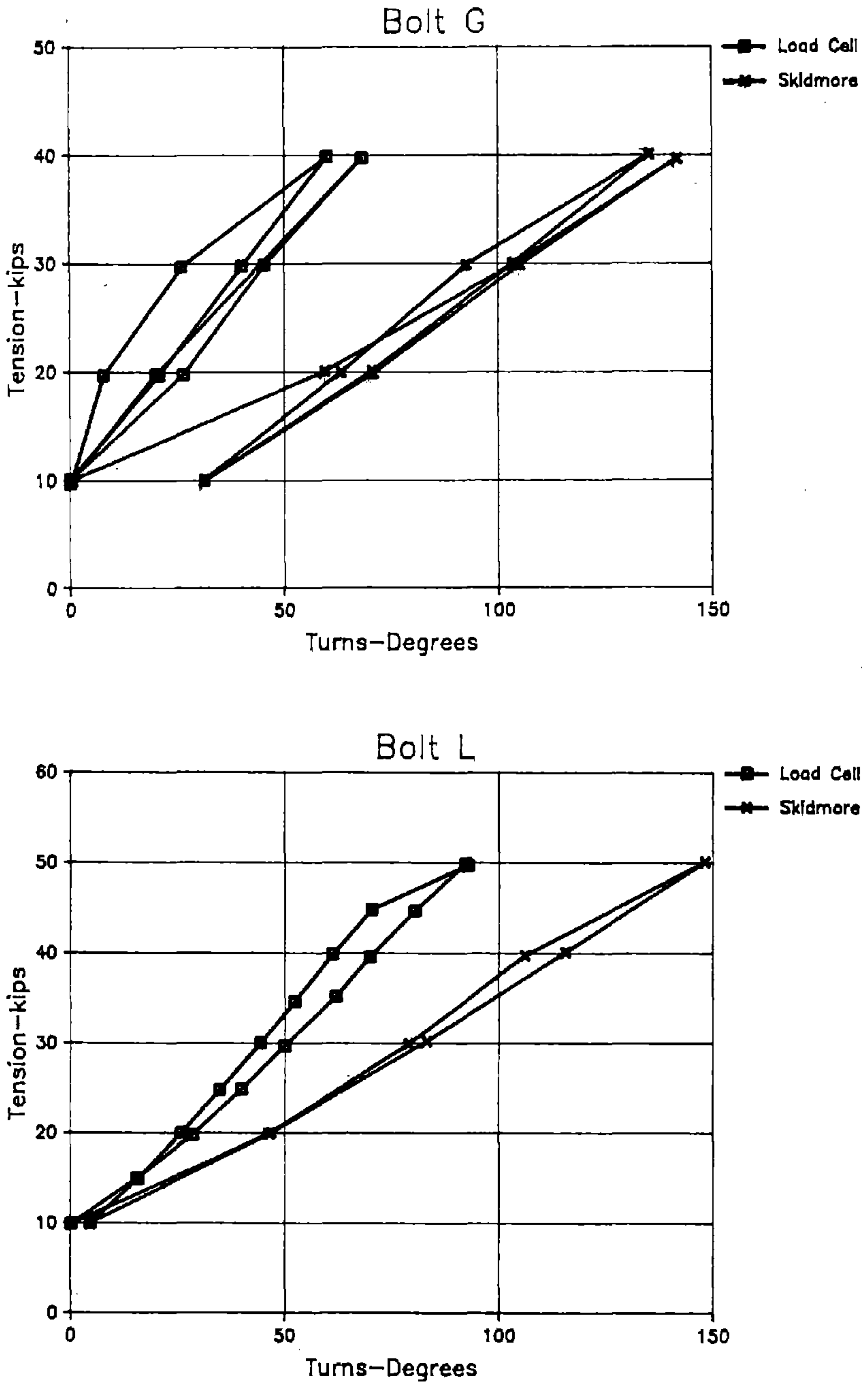


Figure 27. Bolt tension - nut rotation in elastic range.

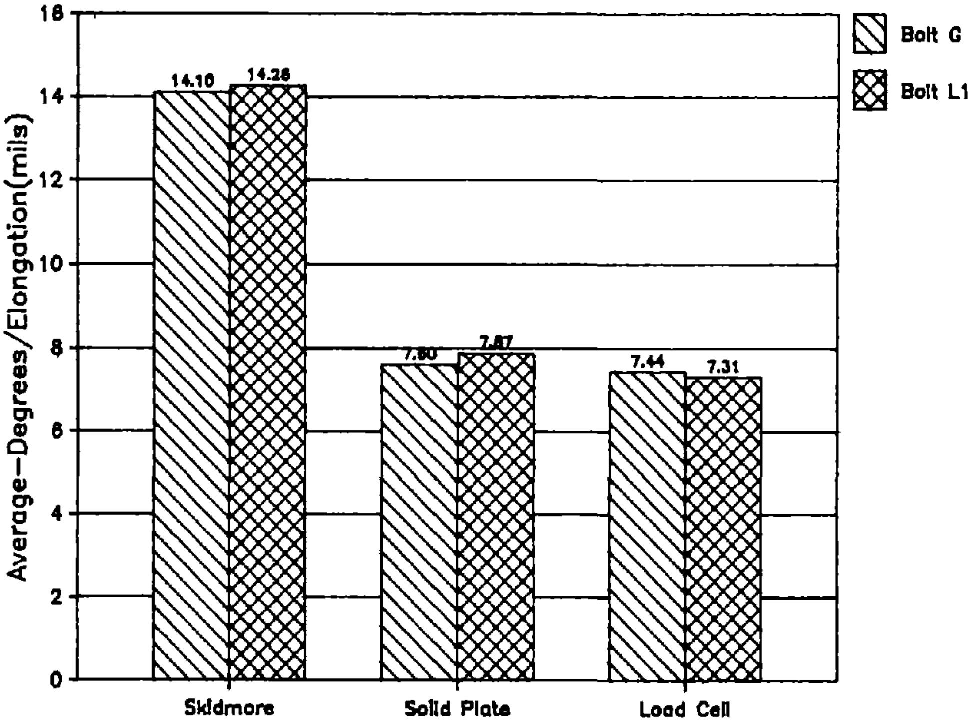


Figure 28. Relative stiffness of test setups.

Consequently, the turns to minimum tension and turns to failure recorded using the load cell to measure bolt tension are indicative of bolt behavior in an actual compacted joint in a structure or in the ASTM required rotation-capacity test.

The total turns to failure of a bolt tested in the Skidmore, however, will be less than twice that of a bolt tested to failure using the load cell or in a solid plate. When the bolt is tested to failure, the bolt normally exhibits a relatively flat tension-elongation curve after reaching its yield load. The stiffness of the load indicating device does not influence nut rotation-bolt elongation in this flat range. The bolt tension does not undergo significant change in this plateau region; consequently, the load on the material within the grip of the bolt is not increased. If the load indicating device and other material in the grip is elastic, then it will not in a Skidmore and a solid plate occur primarily in the initial elastic region. The difference in total turns to failure will be a function of the shape of the tension elongation curve, particularly the ratio of the total elongation at failure to the elastic elongation. A bolt with little ductility, a small ratio of total to elastic elongation, will exhibit the greatest percentage difference in the turns to failure between a test in a Skidmore versus a solid plate. A more ductile bolt will have a smaller percentage difference. For the response shown in figure 24, the turns to T_{max} would be increased by approximately 100 degrees if tested in Skidmore for the 5-in (127 mm) length assuming the load cell is twice as stiff in a Skidmore. Similarly, for the 3-in long (76 mm) bolts tested in a Skidmore, the turn data in the inelastic range would have to be reduced by approximately 60 degrees to give approximate turn data for a load cell (solid plate).

CHAPTER 4. LABORATORY TEST RESULTS

A total of 385 laboratory experiments were conducted to document both bolt and fastener assembly properties and installation behavior. Ninety-two were direct tension tests and 293 were torque-tension-turn tests. The purpose of the tests were to determine what combinations of commercial lubricants, bolt and nut strength, and fit between the nut and bolt give satisfactory behavior of the bolt-nut assemblage and vice-versa. Questions such as mixing of hot dip and mechanically galvanized products in bolt-nut assemblies were addressed. A major objective of this study was to evaluate the performance of both black and galvanized bolts installed and tested according to current practice standards and recognized test procedures.

Performance Concepts for High Strength Bolts

In order to develop design criteria for bolts it is important to define the range of fastener usefulness and to provide minimum requirements for strength and ductility which will ensure proper installation and thus satisfactory performance of the connection.

In developing criteria which will ensure a satisfactory performance of the connection, the definition of "satisfactory" must first be established. In slip critical connections bolts are required to maintain the necessary clamping force between the joined elements and thus ensure the transfer of forces through frictional resistance. It is thus of paramount importance that:

- The bolts are pretensioned to required values.
- The bolts have sufficient deformation capacity without a substantial reduction in strength.
- The bolts do not fail by stripping.

While various methods have been developed to ensure proper pretension loads, the accuracy and dependability of these methods varies with the type and surface condition of the bolts and bolted material, as well as, the workmanship employed in the installation process. The commonly used methods require one or more of the following:

- A predetermined value of torque.
- A predetermined number of turns.
- A predetermined value of elongation.
- A predetermined value of bolt shank strain.
- External devices such as load indicating washers.

A critical evaluation of some of these methods is given in reference 29. All of these methods specify some pre-established limit which must be obtained through physical testing. Current RCSC requirements specify the use of bolt calibrators for this purpose. As a first indication of satisfactory performance, therefore, a bolt tested in a calibrator must reach the required pretension force without failure by either stripping or fracture. The value of torque, elongation, shank strain or number of turns at the require pretension value can then be used in the actual field installation of the bolts.

The second important parameter which has to be taken into account in evaluating a bolt's satisfactory performance is its deformation capacity. This can be measured by the degree of elongation of the bolt to failure, or the number of turns of the nut to failure. There are two main reasons for adequate deformation capacity of bolts. The first relates to the method used for determining the required elongation or number of turns of the required pretension force and the second relates to reuse of bolts.

Tests have shown that there is a variability between the results from a hydraulic bolt calibrator and the results obtained from tests on solid plates representative of the materials in an actual structural connection.[32] Some small differences also exist between the results from various bolt calibrators. As discussed earlier, slightly more turns, 1/6 to 1/4, may be required in a calibrator such as the Skidmore to reach the specified pretension as compared to the number of turns on solid plates. Thus, a field installation conducted on the basis of results obtained through a bolt calibrator (without proper conversion) may result in excessive bolt deformation. The bolt should be able to undergo any such deformation without failure. A similar situation may arise in the field inspection where bolts are required to undergo additional deformation without failure by either fracture or stripping.

The second reason for adequate deformation capacity is the need for reuse of bolts. It has been shown that the cumulative plastic deformation of bolts caused by successive torquing and re-torquing of bolts results in a substantial decrease in the pretension capacity of bolts.[13] Although current specifications allow for reuse of A325 black bolts one time, their capacity could drop below the required preclamping force if they are galvanized. Also, the requirement that a bolt be subjected to an additional twist of the nut during inspection could lead to a deterioration of the bolt's pretension capacity without actual fracture of the bolts. At a high number of turns of the nuts, the possibility of thread stripping increases - a condition which is more difficult to detect and should be avoided. Thus, to prevent an undesirable reduction in the preclamping force, either upon reuse of bolts or during inspection, the following criterion for satisfactory performance was imposed: The reduction in a bolt's capacity should not exceed 10 percent of its ultimate after 1-1/4 turns from snug in a test conducted on a Skidmore-Wilhelm gage (1 turn in 20 lid plates). An example of satisfactory performance of a 7/8-in (22 mm) A325 bolt in a Skidmore-Wilhelm calibrator on solid plate is given in figure 29.

Effect of Lubricants

A limited study was undertaken in order to determine the efficiency of various products available for lubrication of bolt threads. The lubricants included commercially available soluble wax lubricants typically used on galvanized nuts, a high performance molybdenum lubricant, an antiseize

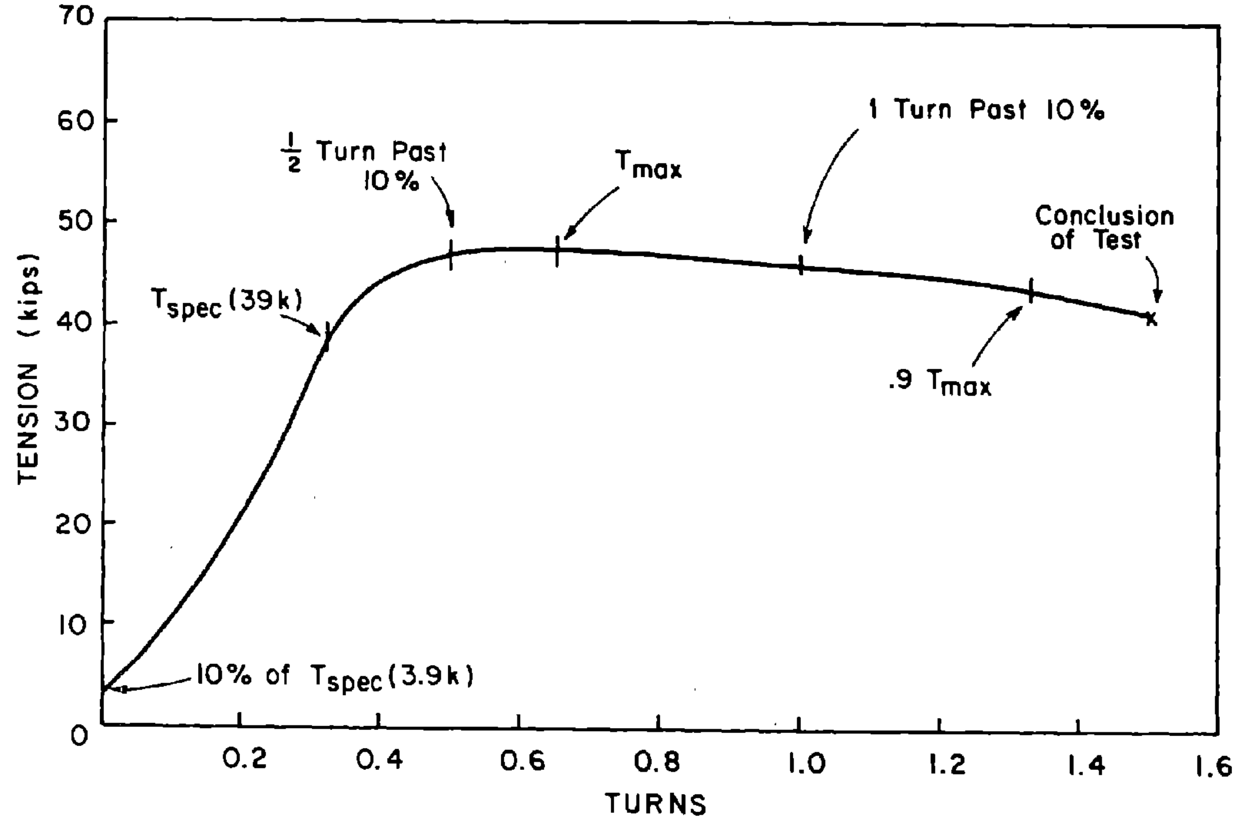


Figure 29. Satisfactory performance of the bolt-nut assembly.

compound, and a stick wax. In addition the influence of the amount of dilution of the water soluble waxes was examined.

A code was used to identify the lubrication condition used in each test. This code will be used in the presentation of the data. The code for the lubrication conditions is shown in table 5. "Weathered" specimens were immersed briefly in water and then set outside for 24 hours. The process was repeated once again in 24 hours. This was to simulate reasonable on-site exposure.

<u>Initial Lubrication Study</u>. The influence of the various types of lubrication upon bolt behavior was studied experimentally using the E bolts and the E nuts (7/8-in (22 mm) A325 hot dipped galvanized bolts and nuts). The results of this initial experiment are shown if figure 30. The data plotted in figure 30 are the average of three replicate specimens. The largest

Table 5. Lubrication study code.

Lubrication Code	Lubricant	Remarks
AR	As received	
W	As received	Weathered
C	Cleaned	
LA	C5-A Antiseize	colloidal copper grease
LJ0	Jon Cote 639	commercial wax-undiluted
LJ1	"	1 part lub to 1 part H_2O
LJ1-D	"	1 part lub to 1 part H_2O distilled
LJ3	"	1 part lub to 3 parts H_2O
LJ3	"	1 part lub to 3 parts H_2O distilled
LJ0-W	"	weathered after LJ0
LM0	MacDermid-1186	commercial wax-undiluted
LM1	"	1 part lub to 1 part H_2O
LM3	"	1 part lub to 3 parts H_2O
LM4	"	1 part lub to 4 parts H_2O
LM0-W	"	weathered after LM0
MOL	Molykote G-n Paste	molybdenum disulfide paste
WX	Johnson #140	stick wax

bolt tension, largest number of turns to failure, and lowest torque occurred when the nut was lubricated with the molybdenum lubricant. The as-received bolt had the smallest bolt tension, smallest number turns to failure, and the highest torque. The stick wax and the two commercial water based wax lubricants produced about the same behavior.

The general trend exhibited in the data is that lubrication that produces lower torque also produces higher tension and bolt ductility (the number of turns to failure). The torque for a given bolt tension is a good indicator of the efficiency of the lubricant. A large torque reduces the bolt strength since the bolt is subjected to a combined state of stress consisting of tension and shear. This combined state of stress reduces the maximum tension that can be attained and reduces the ductility of the bolt.

The results in figure 30 also show that the as-received bolts performed very poorly. It does not appear that the nuts were lubricated. The torque required for the as received bolts for a half of a turn was over 1000 ft-lbs (1355 N-m). The commercial wax lubricants decrease the torque by 50 percent. Bolts like those supplied without an effective lubricant can cause installation problems in the field. The equipment generally used for the installation of 7/8-inch (22 mm) A325 bolts would not have the torque capacity to properly tighten these bolts. In addition, if the equipment has the torque capacity, the low ductility of the bolts could cause them to twist off during installation.

<u>Commercial Water Soluble Wax Study.</u> In order to select a water soluble wax for use on the nuts included in this study, a detailed evaluation of the Jon Cote 639 and MacDermid 1186 lubricants was performed. The lubricants were tested using 7/8-in (22 mm) A325 mechanically galvanized bolts and nuts from Lot D. The manufacturer's literature for both wax products did not give specific recommendations for the dilution of the products. Both lubricants are water soluble. The influence of the amount of dilution by water of the products was included in this experiment. Tap water was used to dilute the waxes. A side experiment using distilled water showed no influence of the type of water upon the lubricants performance.

The Jon Cote 639 was tested full strength, LJ0; diluted with one part water, LJ1; diluted with three parts water, LJ3; and weathered after full strength lubrication, LJ0-W. The MacDermid lubricant was tested full strength, LM0; diluted with one part water, LM1; diluted with four parts water, LM4; and weathered after full strength lubrication, LM0-W. The weathering was simulated by immersing the nuts in water. This was done once each day for 2 days. The

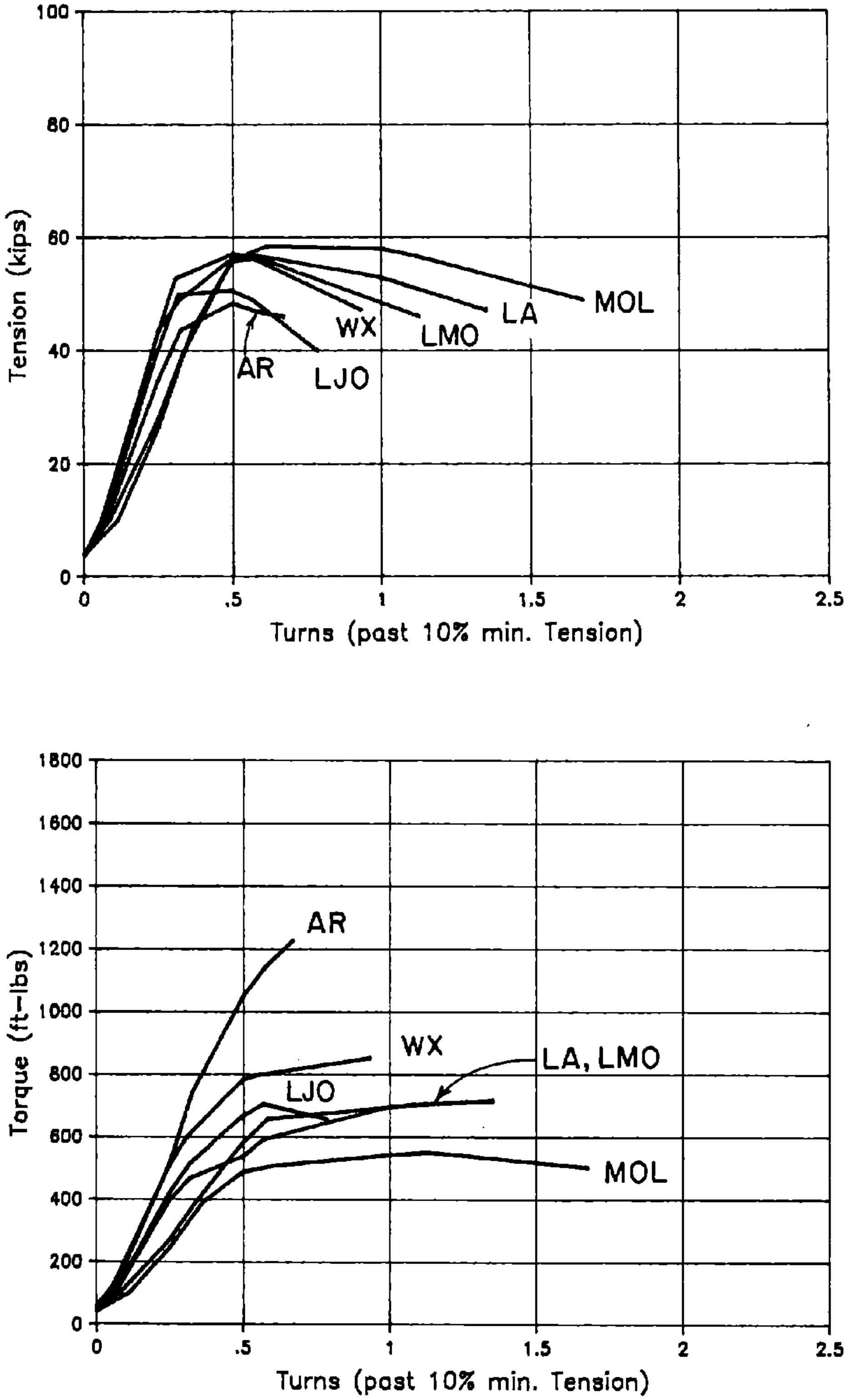


Figure 30. Lubrication experiment - E assembly (HG).

intent of this weathering was to simulate the exposure of the lubricated nuts to rain water at a job site.

The results of the tests are summarized in figure 31. The results shown are the average of three tests for each lubrication condition. The upper bar graph gives the average torque of the bolts at the snug condition of 10 kips (44 kN), minimum specified tension of 39 kips (173 kN), 43 kips (191 kN), 10% above the minimum specified tension, and the maximum torque during the tests. In general the torque required to produce a given tension increased as the lubricants were diluted. Weathering did not significantly change the torque-tension performance of either lubricant. The torque at the higher bolt tensions was larger for the MacDermid than the Jon Cote lubricant.

The lower bar graph shows the number of turns to produce the required bolt tension. The 10 kip (44 kN) tension was used as the snug tight starting point for the turns. The required tension was produced in less than one half of a turn for all the bolts. The turns to failure using both the 10 kip (44 kN) tension and 4 kip (18 kN) tension as a starting point for the turns are also shown. The 4 kip (18 kN) starting point is 10 percent of the required installation tension specified in ASTM A325 for the turn test of galvanized bolts. All of the results satisfied the one turn requirement of ASTM A325 using the 4 kip starting point. All bolts except those where nuts were lubricated with the MacDermid product diluted with 4 part water also reached more then one full turn from the 10 kip (44 kN) snug tension before failure.

The results indicated that the two commercial lubricants tested provided sufficient lubrication even when diluted with water. The lubricants were not significantly degraded when the coated nuts were weathered. The Jon Cote 639 diluted with one part of water was selected for use as a lubricant for all the bolts tested in the project. The Jon Cote was selected since it produced a 20% lower maximum torque then the MacDermid lubricant. The diluted lubricant rather than the full strength was selected for use since it was felt that commercial users would dilute the wax for economy.

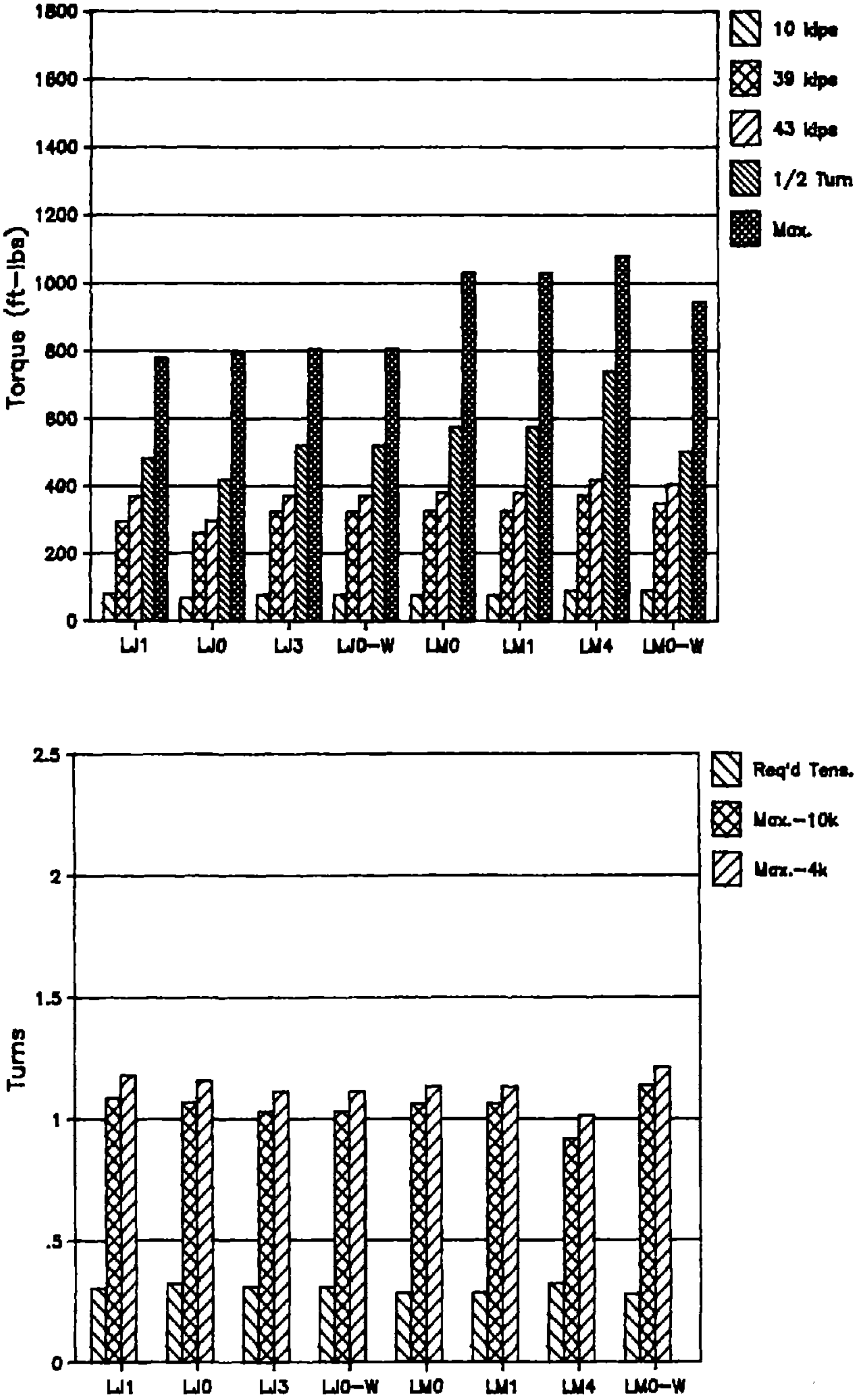


Figure 31. Water soluble commercial wax results - D assembly (MG).

Torque-Tension Tests of Fastener Assemblies

Four lubrication conditions were selected for testing each lot of bolts and nuts. The bolt nut assemblies were tested in the as received condition,AR; the cleaned condition,C; as received weathered condition,W; and cleaned followed by lubrication with Jon Cote 639 diluted with one part water,LJ1. Three replicate tests were performed for each lubrication condition. The difference between the as-received condition and the cleaned condition provides an indication of the efficiency of the lubrication applied to the nuts. The bolts and nuts were cleaned in acetone to remove all the lubrication on the threads and turning surface of the nuts. The tests of the as-received assemblies after they had been weathered was to determine the significance of rain water exposure at the job site upon the performance of the fastener.

The replicate results were developed by taking the average of the tension or torque of the three results at 0.05 turn increments. The starting point for the turns was taken as the number of turns at 10 percent the required pretension in the bolts. Figure 32 shows the three individual results for the A bolts and nuts tested in the as received condition. The scatter in the test results for these three replicate specimens is quite small. This was typical of all the tests. The average of the tests will be used in the following presentation of the test results.

The average results of each bolt and nut assembly tested is shown in table 6. The results shown include the additional lubrication conditions tested in the initial lubrication experiments.

A325 Mechanically Galvanized. The results of the D and F assemblies are shown in figures 33 and 34. Both of these assemblies failed to reach 1 full turn past the 10 percent required tension starting point and showed no significant difference between the AR, C, and W conditions. These results indicate that neither assembly had been lubricated and that the required ASTM turn test had not been performed by the supplier. The F assemblies did not

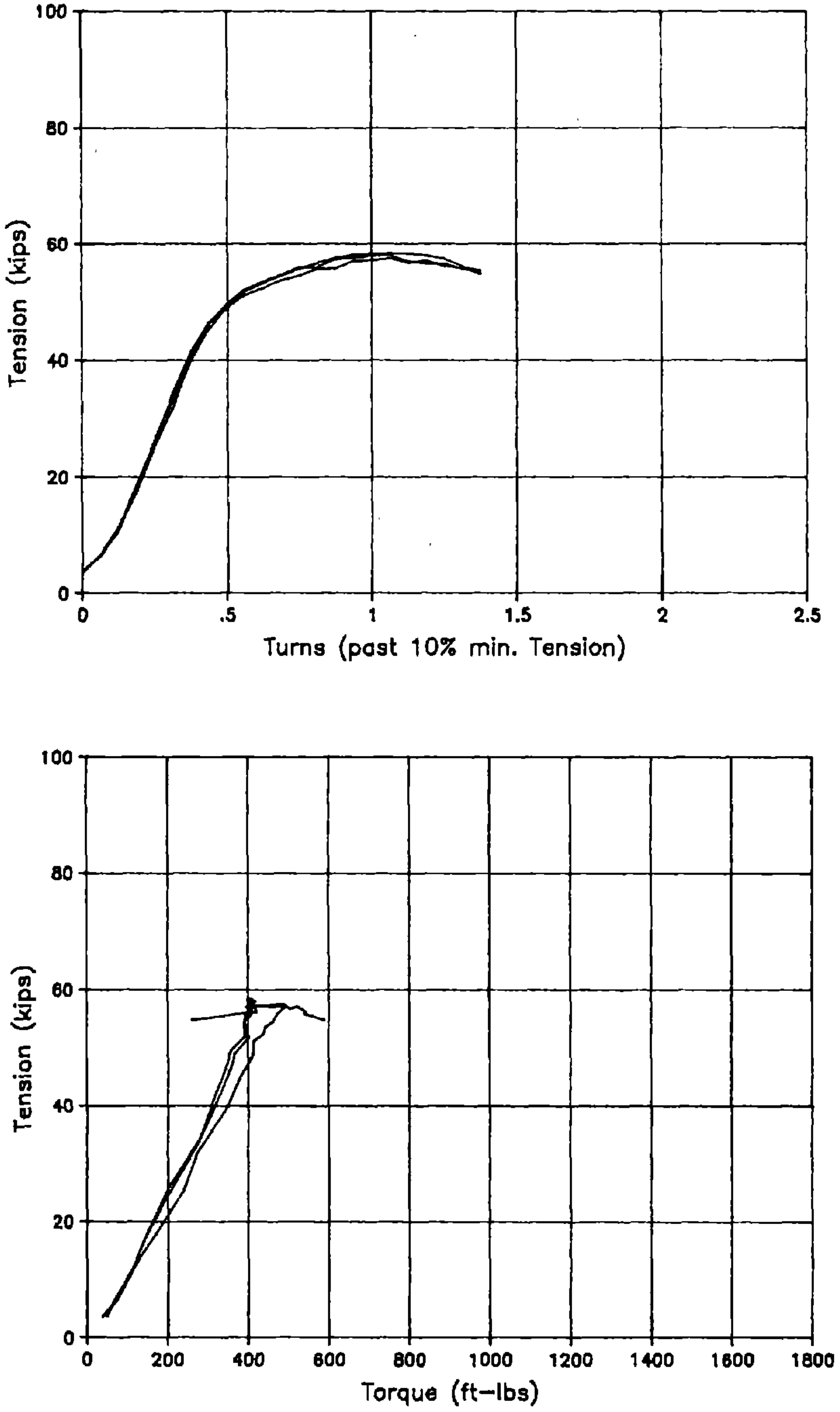


Figure 32. Replicate results - A assembly - as received (A325-B).

Table 6. Summary of torqued tension tests.

				Tension		Torque					Turns		
Bolt	Nut	Lub.	Length in.	1/2 Turn kips	Max. kips	10 kips ft-lbs	Spec.T ft-lbs	1.1xT ft-lbs	1/2 Turn ft-lbs	Max. ft-lbs	Spec.T	Max. (10 k)	Max. .1xT
						A325-Mechanically Galvanized							
D	D	AR	5.0	40.4	40.6	203	987	N/A	1,046	1,160	.524	.77	.85
D	D	W	5.0	40.7	42.3	167	831	N/A	1,063	1,193	.540	.74	.82
D	D	C	5.0	41.0	41.0	234	1,059	N/A	1,059	1,170	.539	.69	.77
D	D	LJ1	5.0	49.9	50.0	80	295	369	483	778	.307	1.09	1.18
D	D	LJ0	5.0	53.7	54.1	67	262	297	419	792	.326	1.07	1.16
D	D	LJ3	5.0	49.0	49.6	78	324	371	521	805	.312	1.03	1.11
D	D	LJ0-W	5.0	49.0	49.6	78	324	371	521	805	.312	1.03	1.11
D	D	LM0	5.0	52.7	50.6	77	326	380	577	1,030	.287	1.06	1.13
D	D	LM1	5.0	50.6	50.6	77	326	380	577	1,030	.287	1.06	1.13
D	D	LM4	5.0	48.7	48.7	90	375	418	740	1,080	.326	.92	1.01
D	D	LM0-W	5.0	55.1	55.1	92	349	405	504	945	.283	1.14	1.21
D	D	LA	5.0	48.0	49.0	90	362	408	559	858	.220	1.18	1.25
D	D	LJ1-D	5.0	48.0	50.0	80	326	369	467	778	.246	1.08	1.18
D	D	LJ3-D	5.0	49.0	49.0	78	324	378	506	803	.228	1.02	1.11
F	F	AR	5.0	34.7	34.7	384	N/A	N/A	N/A	1,237	N/A	.26	.34
F	F	W	5.0	32.5	32.5	348	N/A	N/A	N/A	1,237	N/A	.32	.46
F	F	C	5.0	34.3	34.6	318	N/A	N/A	N/A	1,160	N/A	.35	.46
F	F	LJ1	5.0	60.0	61.5	133	609	701	1,177	1,369	.204	1.52	1.60
F	F	LA	5.0	54.3	56.5	93	331	361	475	909	.222	1.60	1.71
						A325-Hot Dipped Galvanized							
I	I	AR	5.0	53.1	54.6	102	353	402	533	681	.178	.96	1.02
I	I	W	5.0	52.5	53.0	113	381	415	555	674	.178	.94	1.00
I	I	C	5.0	51.9	53.0	103	377	411	557	708	.179	.97	1.03
I	I	LJ1	5.0	54.2	56.7	100	315	331	442	521	.181	1.18	1.24
K	K	AR	5.0	61.8	65.1	83	279	305	403	584	.184	1.68	1.76
K	K	W	5.0	63.2	66.9	86	279	300	400	474	.176	1.28	1.35
K	K	C	5.0	62.1	65.9	89	306	327	423	587	.177	1.35	1.42
K	K	LJ1	5.0	61.8	65.1	93	320	342	459	701	.178	1.33	1.40
E	E	AR	5.0	48.3	49.8	142	454	683	1,110	1,240	.222	.60	.67
E	E	C	5.0	42.2	43.3	199	957	1,007	1,153	1,187	.404	.47	.53
E	E	LJ1	5.0	52.8	53.3	104	390	448	624	677	.230	.81	.86
E	E	LJ0	5.0	50.6	51.5	112	392	438	662	745	.174	.72	.78
E	E	LM0	5.0	55.7	56.8	106	392	397	578	712	.253	1.04	1.12
E	E	LA	5.0	56.3	56.9	108	362	407	537	744	.183	1.43	1.45
E	E	WX	5.0	54.0	54.5	144	510	573	942	954	.174	.87	.93
E	E	MOL	5.0	56.0	58.5	101	353	385	487	547	.223	1.56	1.67

Table 6. Summary of torqued tension tests. (continued)

Bolt	Nut	Lub.	Length in.	Tension 1/2 Turn kips	Tension Max. kips	Torque 10 kips ft-lbs	Torque Spec.T ft-lbs	Torque 1.1xT ft-lbs	Torque 1/2 Turn ft-lbs	Torque Max. ft-lbs	Turns Spec.T	Turns Max. (10 k)	Turns Max. .1xT
						A325-Black							
A	A	AR	3.0	52.6	58.1	197	645	699	805	985	.248	1.33	1.43
A	A	W	3.0	52.3	58.7	194	623	653	827	1,217	.277	1.40	1.53
A	A	C	3.0	47.2	48.7	236	888	1,010	1,275	1,557	.278	.90	1.01
A	A	LJ1	3.0	53.7	58.3	159	591	655	936	1,688	.275	1.31	1.42
T	T	AR	4.0	56.7	59.0	138	457	499	630	744	.235	1.96	2.06
T	T	W	4.0	55.8	57.1	150	369	494	623	653	.237	2.00	2.10
T	T	C	4.0	54.0	55.5	156	597	653	717	811	.244	1.52	1.60
T	T	LJ1	4.0	57.8	60.3	96	313	335	467	585	.230	2.09	2.17
H	H	AR	5.0	51.9	53.1	160	425	598	699	896	.252	1.02	1.11
H	H	W	5.0	52.0	52.2	169	558	599	665	777	.273	1.07	1.14
H	H	C	5.0	43.9	44.0	205	911	1,040	1,189	1,277	.307	.40	.48
H	H	LA	5.0	52.1	52.6	112	433	474	562	950	.332	1.05	1.15
						A490-Black							
B	B	AR	3.0	62.3	69.7	204	879	955	1,118	1,611	.346	1.71	1.81
B	B	W	3.0	62.2	67.8	217	768	753	967	1,190	.363	1.34	1.43
B	B	C	3.0	54.3	56.5	259	1,193	907	1,397	1,817	.394	.89	1.01
B	B	LJ1	3.0	62.3	78.2	147	536	568	577	871	.380	1.53	1.65
L	L	AR	5.0	66.0	67.2	161	657	714	839	864	.226	1.14	1.19
L	L	W	5.0	64.7	66.2	180	709	759	853	904	.237	1.13	1.18
L	L	C	5.0	50.8	53.3	239	681	736	1,156	1,227	.104	.71	.75
L	L	LJ1	5.0	68.7	70.0	149	572	624	795	1,019	.227	1.16	1.21
G	G	AR	5.0	66.1	66.8	153	649	685	872	953	.241	.78	.82
G	G	W	5.0	66.5	66.5	151	616	637	735	783	.301	1.13	1.16
G	G	C	5.0	63.8	63.8	154	710	801	1,021	1,210	.312	.70	.77
G	G	LJ1	5.0	67.3	69.3	127	460	501	830	1,071	.188	1.10	1.17
G	G	LA	5.0	63.9	67.4	128	596	647	769	1,087	.282	1.02	1.08
								Mixed-A325 Galvanized					
K	R	AR	5.0	N/A	34.0	319	N/A	N/A	429	1,285	N/A	.52	.61
K	R	LJO	5.0	60.9	64.4	147	615	677	1,035	1,257	.189	1.17	1.24
I	D	AR	5.0	50.2	50.5	180	684	785	983	1,151	.193	.88	.94
I	D	LJ1	5.0	52.3	53.1	117	535	574	817	1,005	.193	1.11	1.16

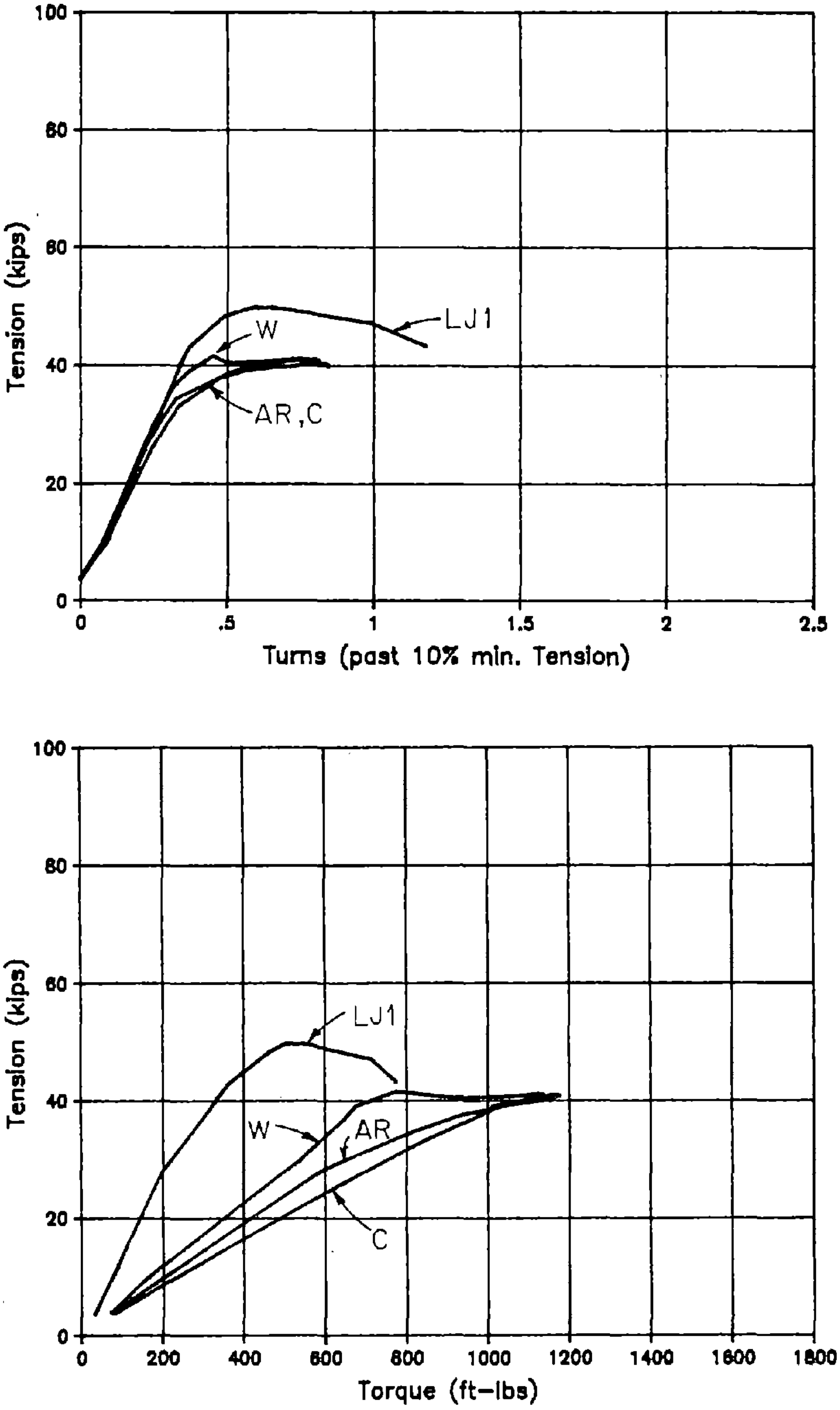


Figure 33. D assembly results (MG).

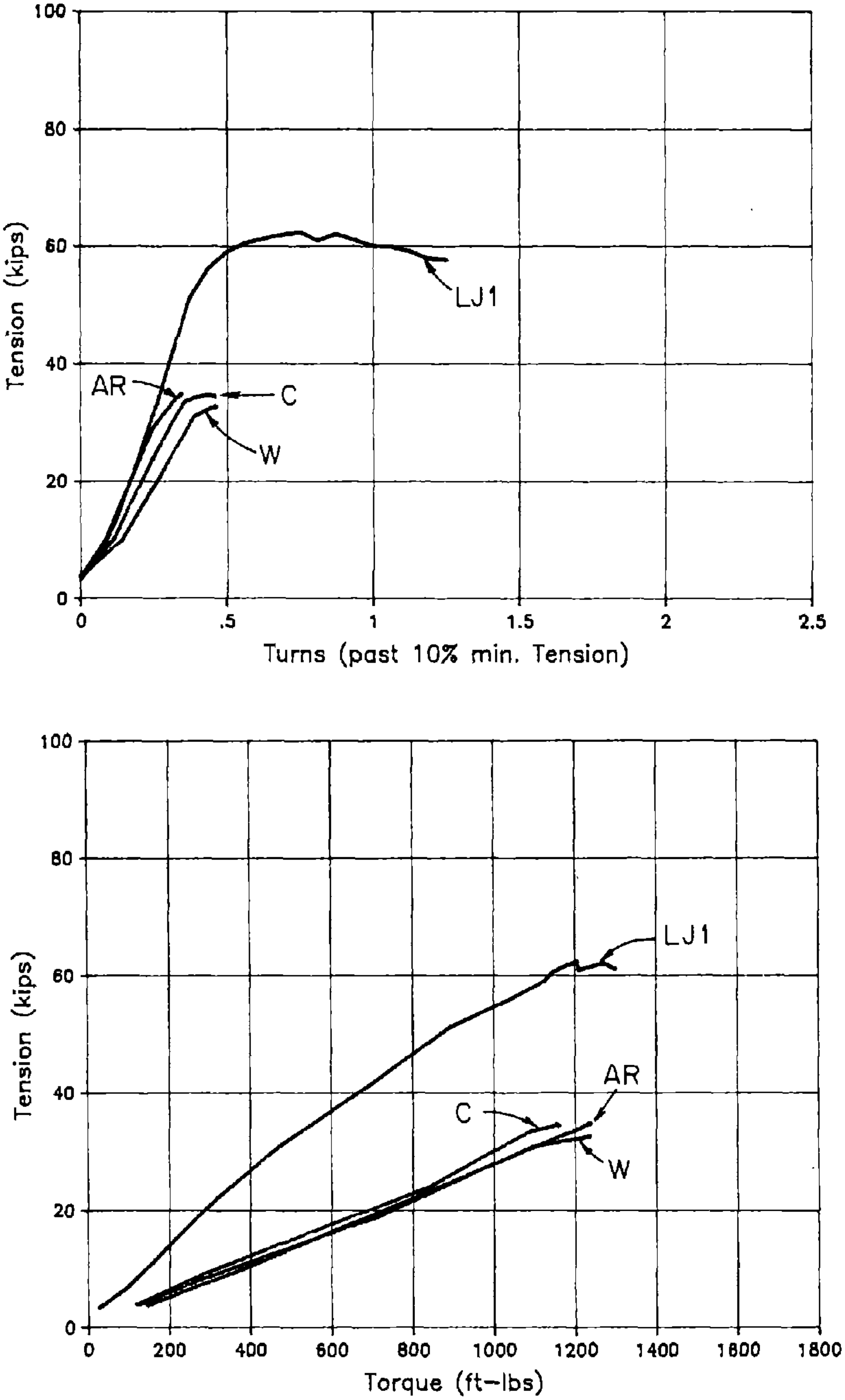


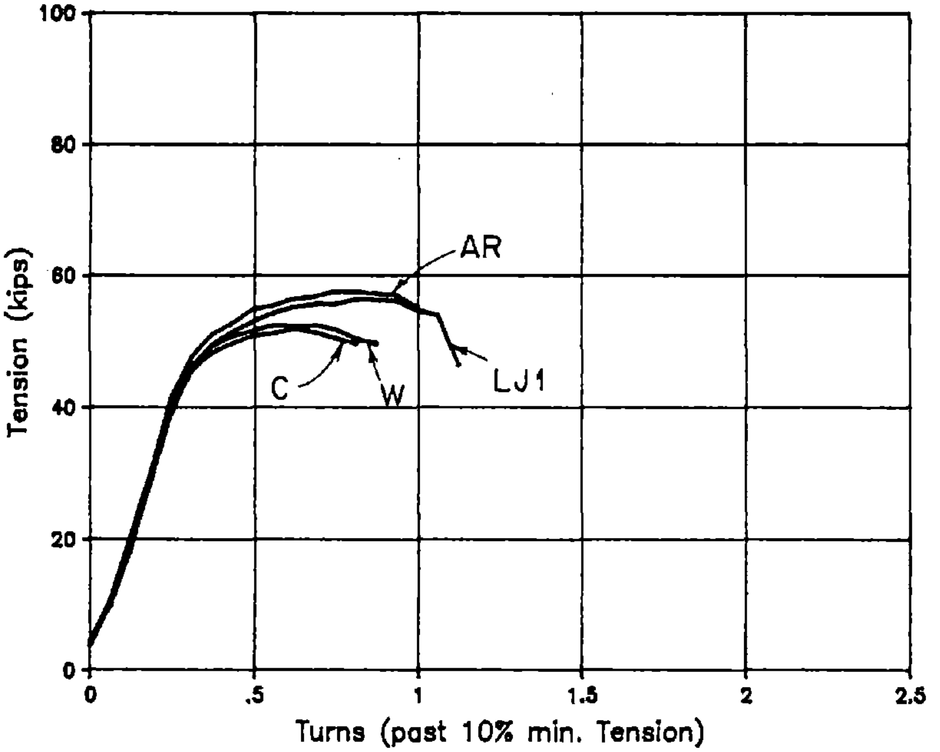
Figure 34. F assembly results (MG).

reach the required pretension after application of 1200 ft-lbs (1630 N-m) of torque, the limit of the test setup.

Both of these assemblies performed well when tested in the LJ1 lubrication condition. The maximum tension increased by 25 percent in the D assemblies and 100 percent in the F assemblies. The turns to failure of the assemblies exceeded one turn.

A325 Hot-Dip Galvanized. The results of the I,K, and E assemblies are shown in figures 35 to 37. The results of these assemblies do not show any dramatic difference between the lubrication conditions. The I and E assemblies show a slight reduction in tension and turns in the cleaned versus the as-received condition. This would indicate that a lubricant was applied to these nuts by the supplier. The K assemblies showed essentially the same behavior for all four lubrication conditions. The K assemblies also produced the maximum tension of all the A325 bolts tested. The E bolts exhibited very poor ductility. The bolts failed before reaching the ASTM required one turn past snug. The torque requirement for the E assemblies was also very high in the as received and clean conditions. The application of the LJ1 lubrication reduced the maximum torque by one half.

A325 Black Bolts. The results of the A, T, and H assemblies are shown in figures 38, 39, and 40. These black bolts performed essentially the same in the AR, W, and lubricated conditions. The assemblies all provided adequate rotation capacity in the as-received condition. The H assemblies produced the lowest ductility. The residual oil present on the bolts was an adequate lubrication. The oil did not appear to be as soluble in water as the bolts tested in reference 12. The water immersion in the weathering simulation did not significantly degrade the performance of the assemblies. Cleaning of the threads drastically increased the torque requirements of the assemblies, reduced the ductility of the bolts, and reduced the maximum tension developed in the tests.



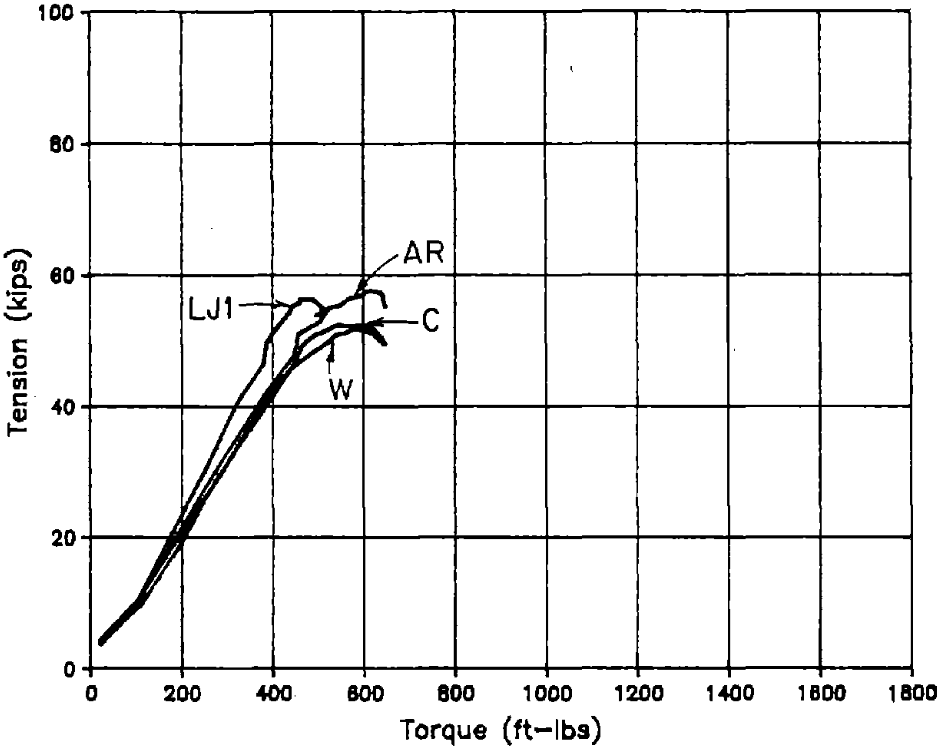


Figure 35. I assembly results (HG).

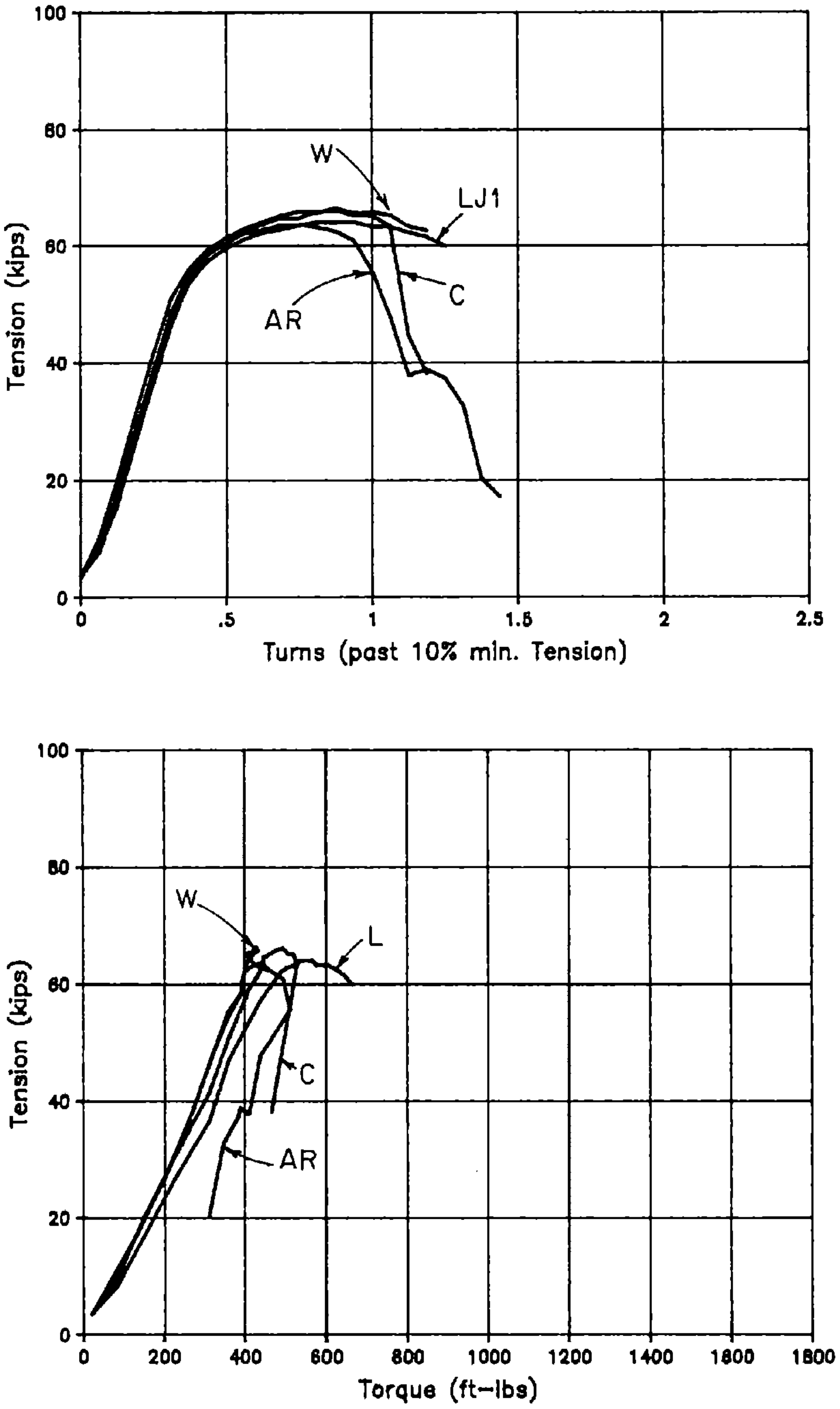
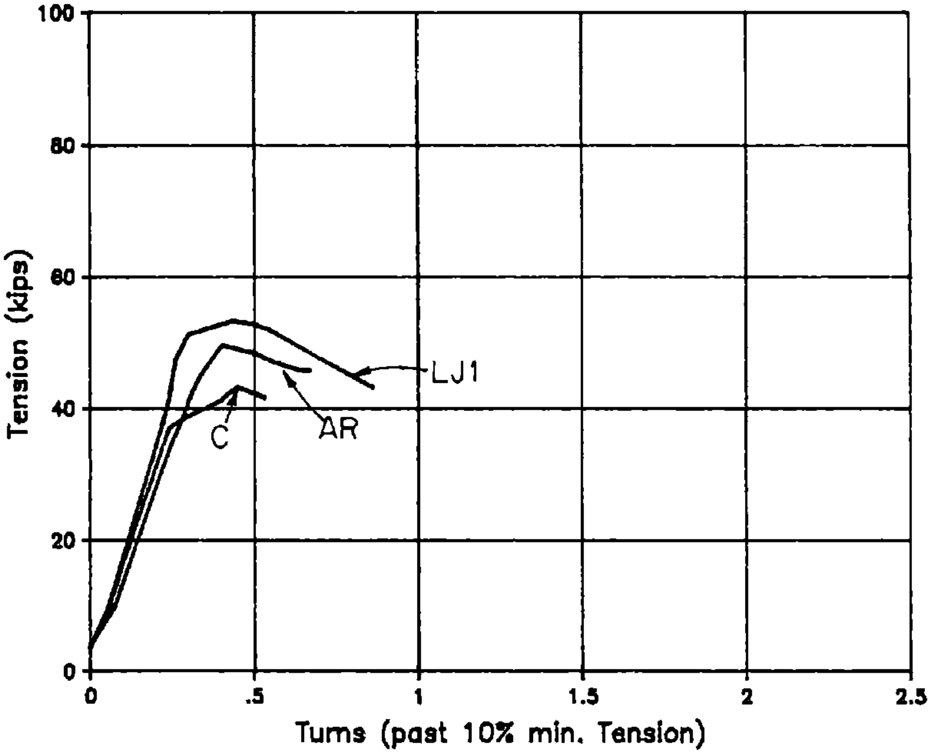


Figure 36. K assembly results (HG).



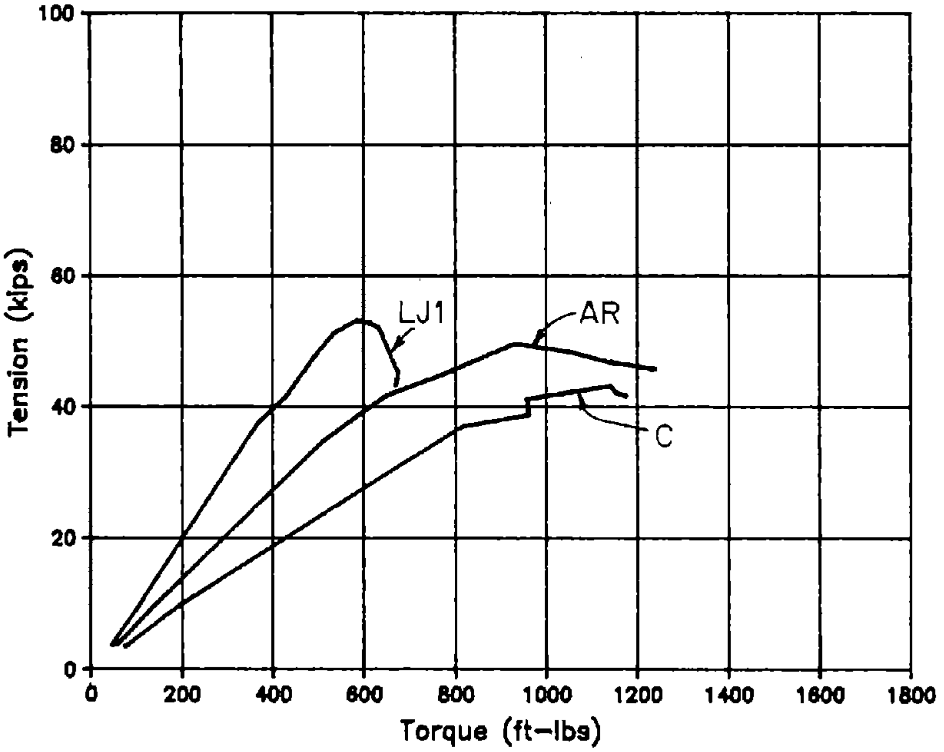


Figure 37. E assembly results (HG).

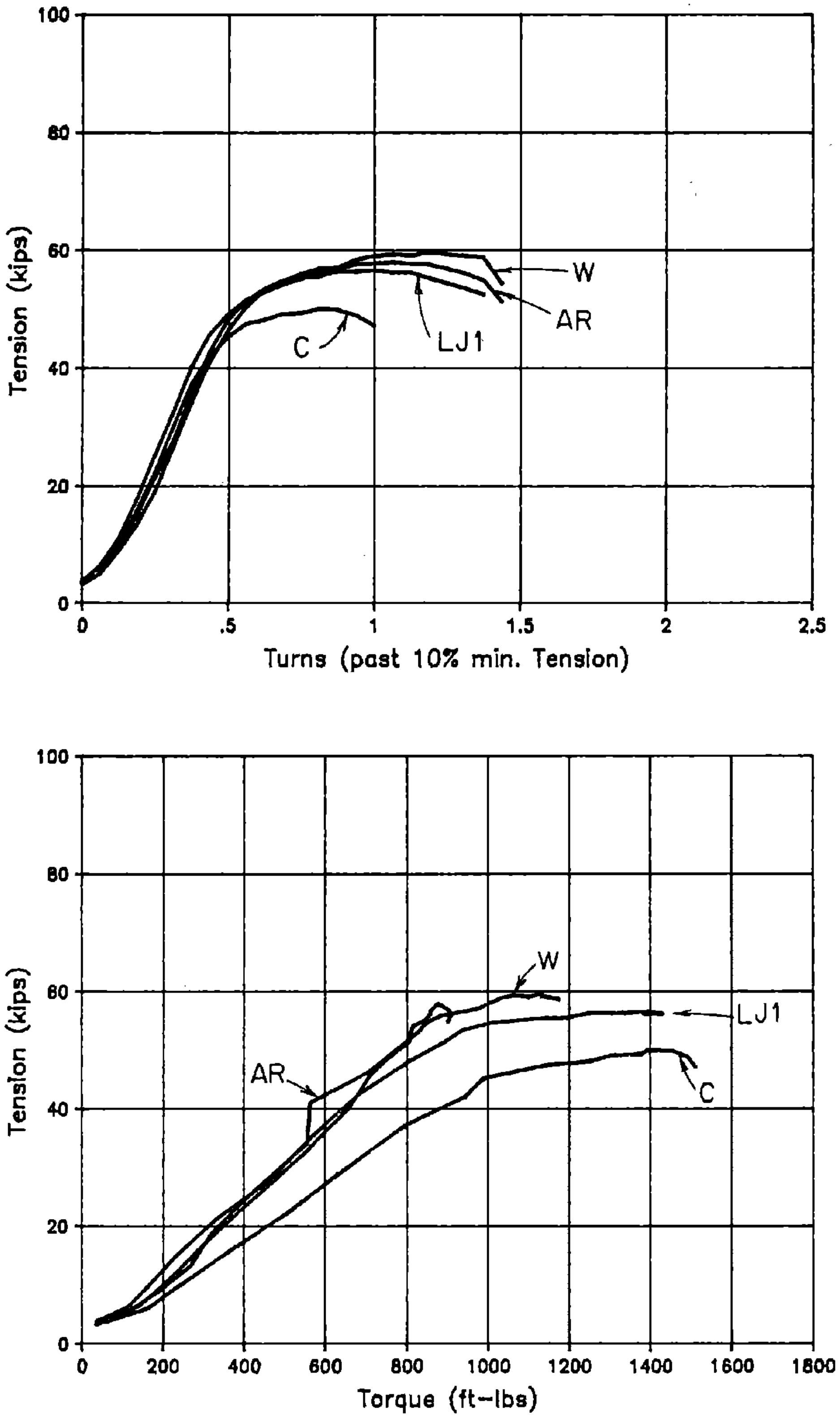
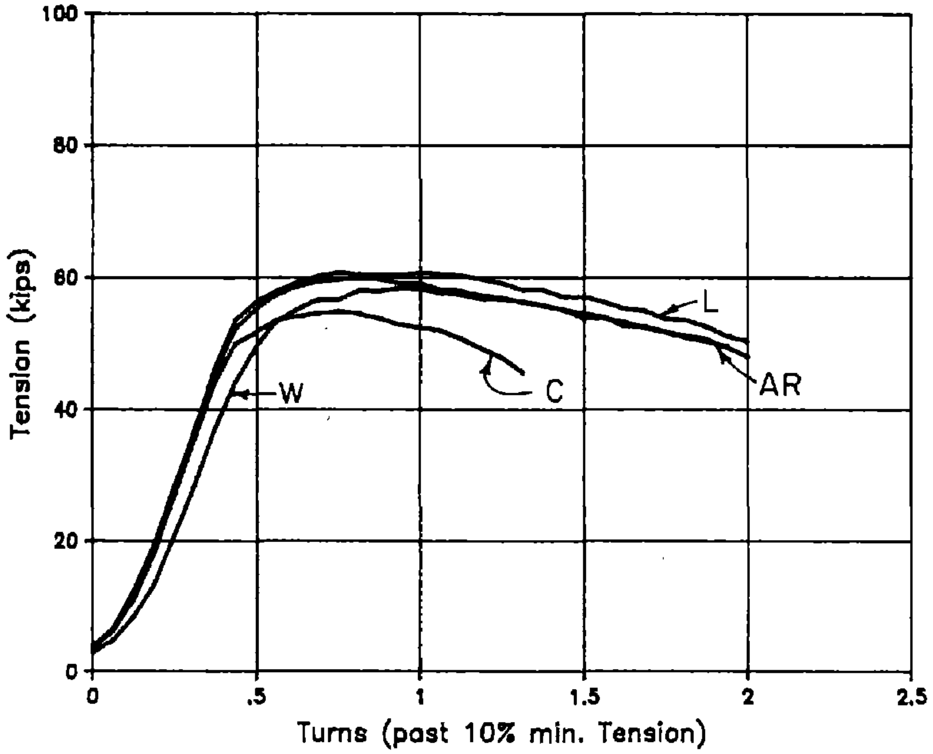


Figure 38. A assembly results (A325-B).



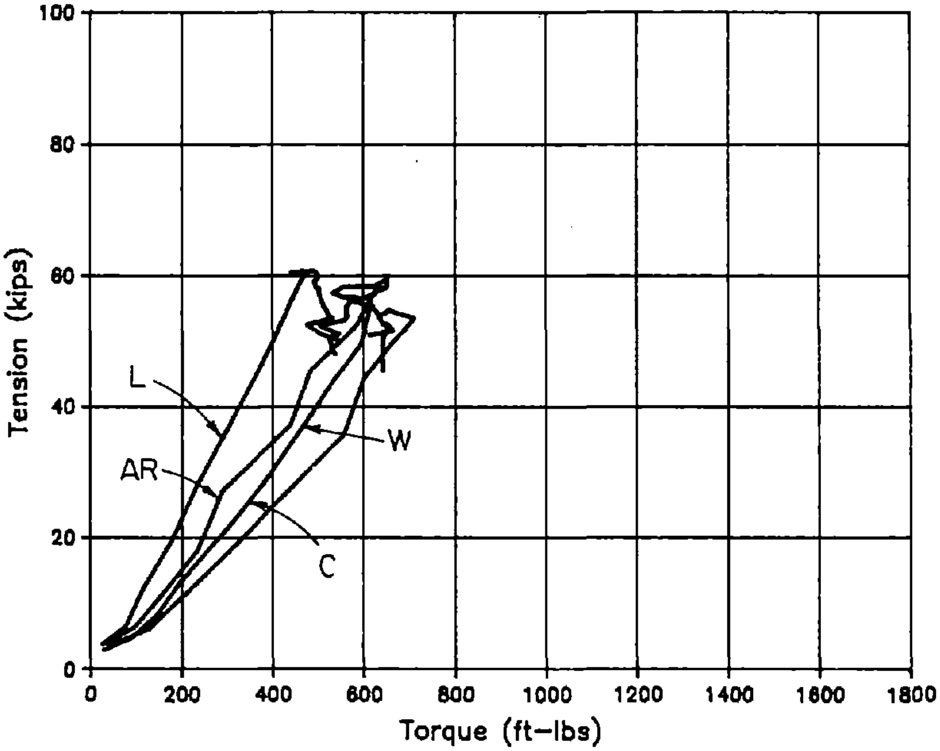


Figure 39. T assembly results (A325-B).

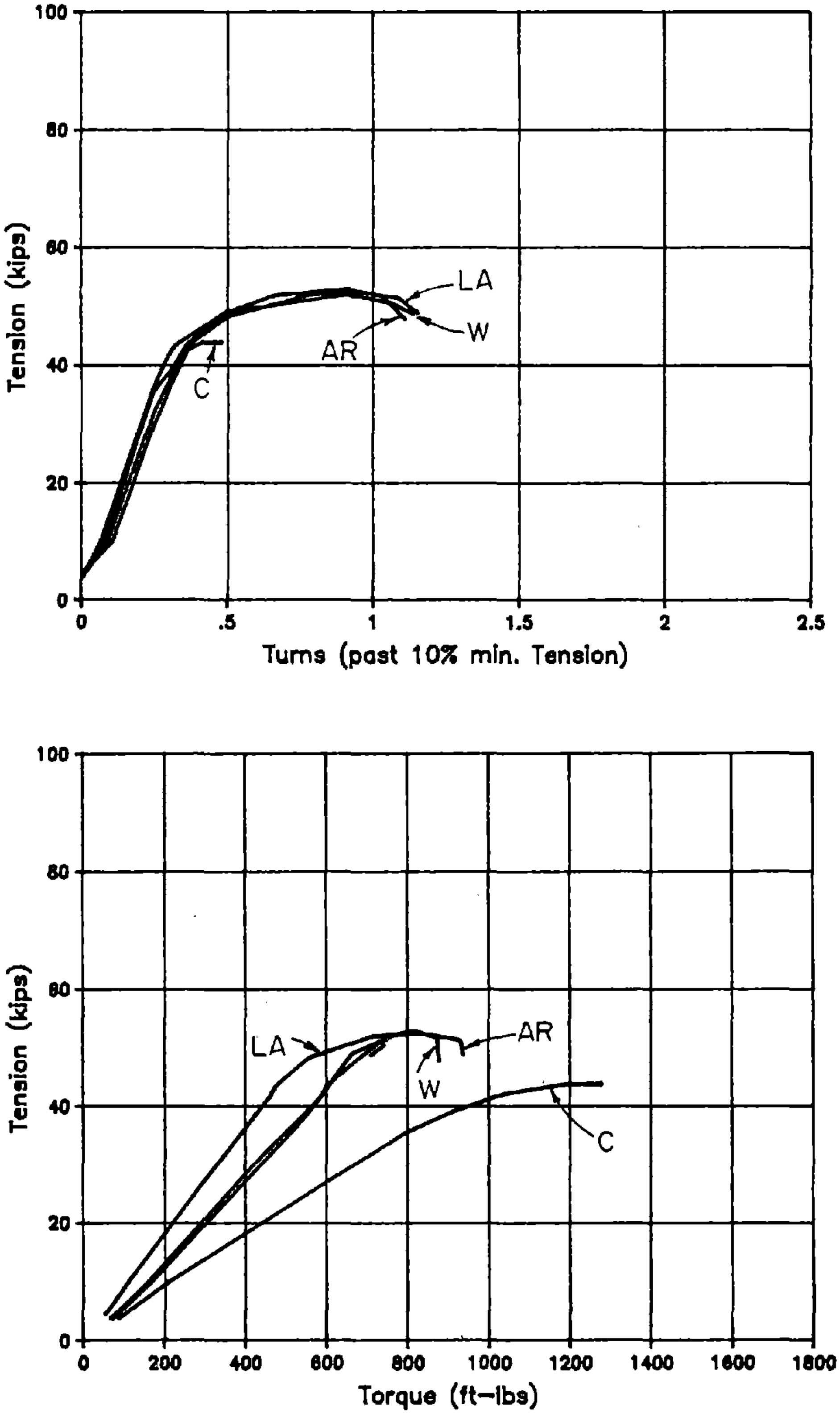
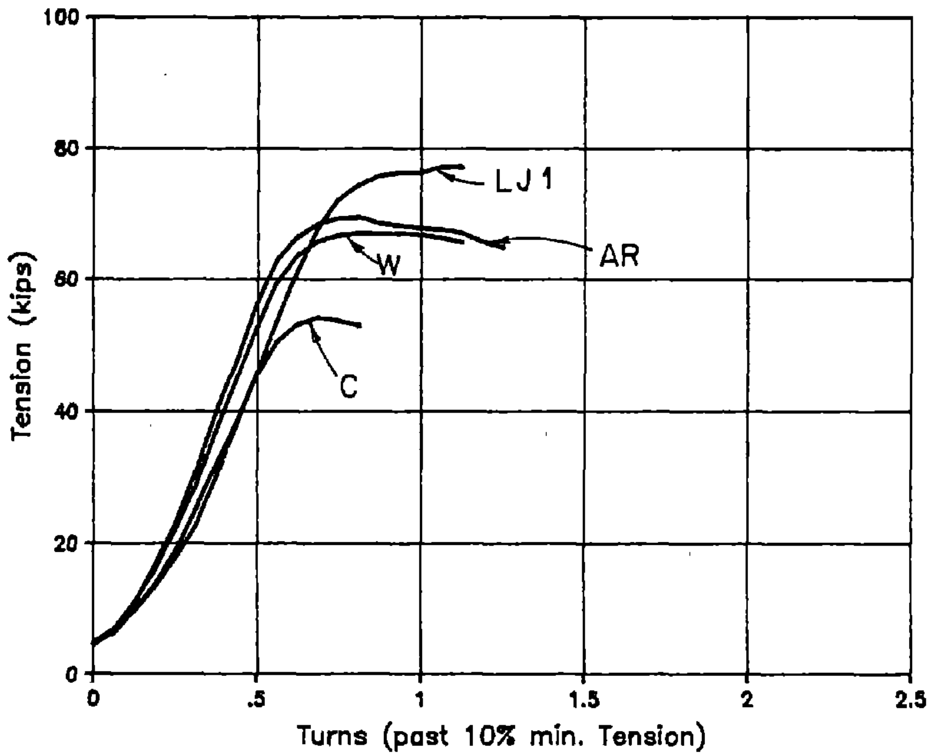


Figure 40. H assembly results (A325-B).

A490 Black Bolts. The test results of the B, L, and G assemblies are shown in figures 41 to 43. These higher strength bolts exhibited lower ductility than the black A325 bolts. The LJ1 lubrication provided better behavior then the AR condition for the B and L assemblies. Cleaning drastically reduced the strength and ductility of the B and L assemblies. The ductility of these bolts was similar to the low ductility of the galvanized A325 bolts.

Mixed Assemblies. The K bolts were tested with the R nuts to determine the influence of thread fit and nut strength upon the behavior of the assembly. Also, the types of galvanized bolts and nuts, were mixed, where hot-dip galvanized bolts with mechanically galvanized nuts were used. Current specifications do not permit mixing on an assemblage but no data are available to indicate that such mixing is detrimental. The results are shown in figure 44. The performance of the assembly was very poor in the AR condition. The required minimum tension was not attained in the test and the test was terminated at 1/2 a turn due to excessive torque. Lubrication provided excellent behavior. It should be noted that the L bolt performed satisfactorily in the AR condition when tested with the nut supplied with that bolt. The difference in the behavior of the bolt with two different nuts indicates the need to have a test in the specifications which includes the testing of the nut and bolt together. Substitution of a different nut which is not properly lubricated may jeopardize the performance of a fastener assembly.

The I bolt was tested with the D nut to look at the influence of thread fit and type of galvanizing upon performance. The I bolt was hot dipped galvanized and the D nut was mechanically galvanized. The results are shown in figure 45. The results indicate that in the lubricated condition the performance was similar to the I bolt tested with the I nut. The difference in the coating method did not significantly change the performance of the assembly as long as the threads in the nut and bolts provided sufficient thread engagement.



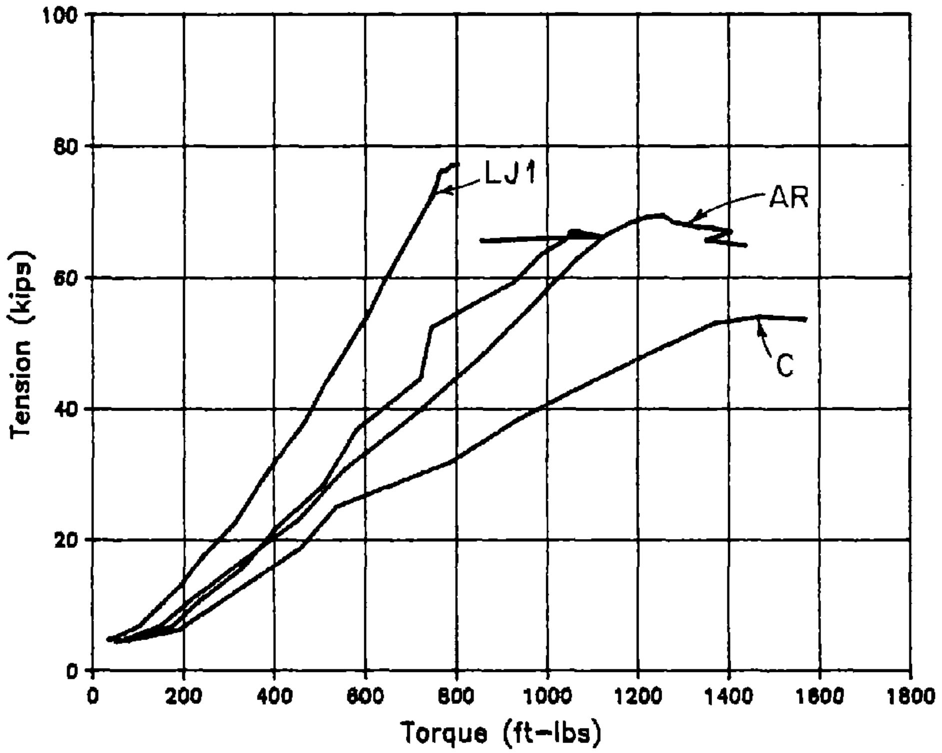


Figure 41. B assembly results (A490-B).

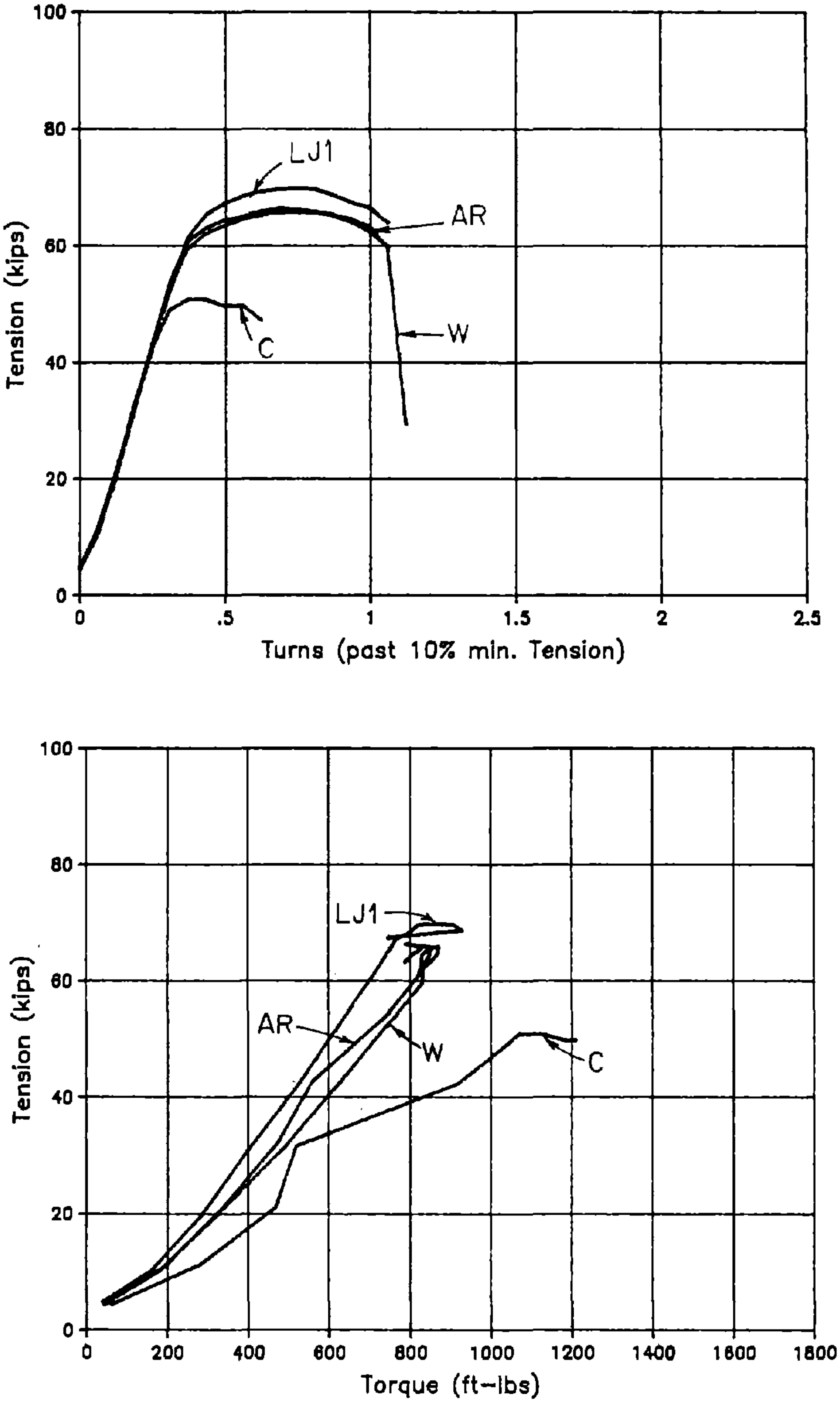
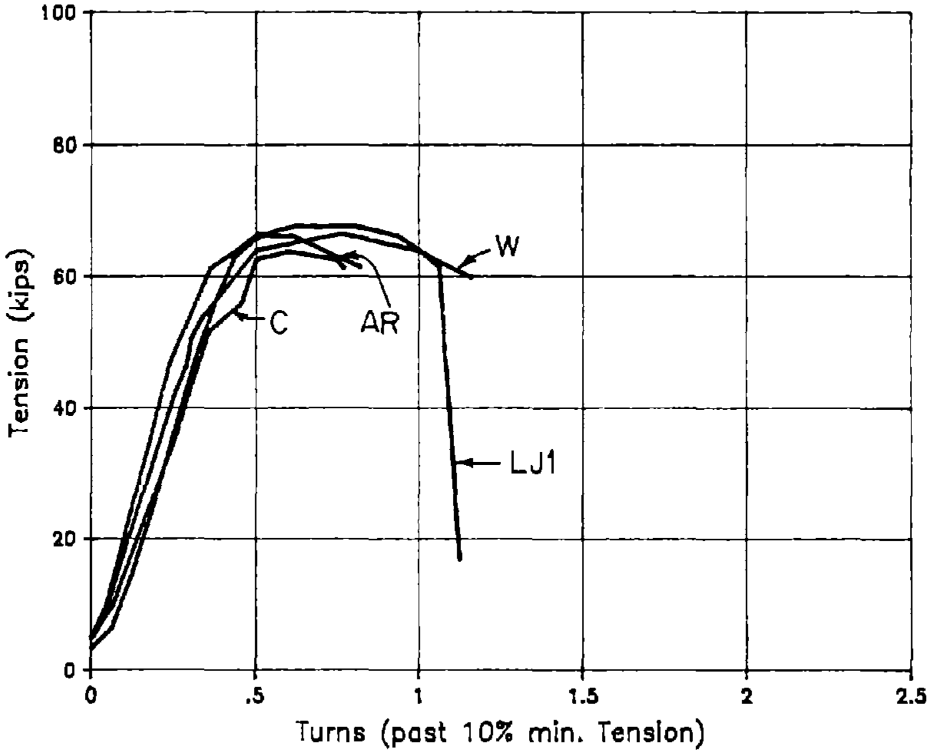


Figure 42. L assembly results (A490-B).



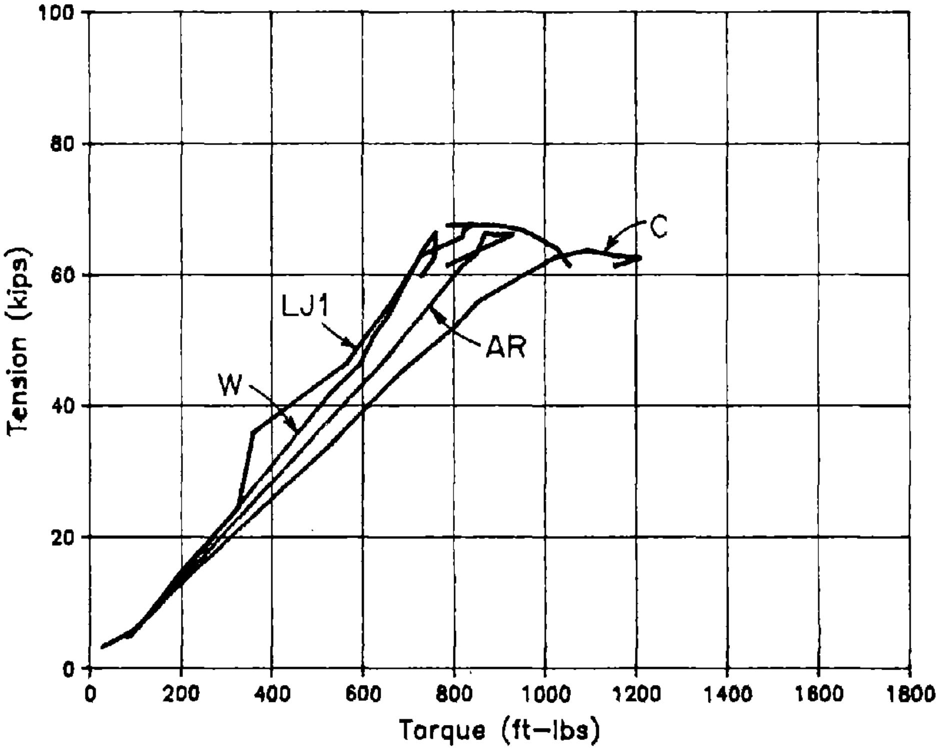
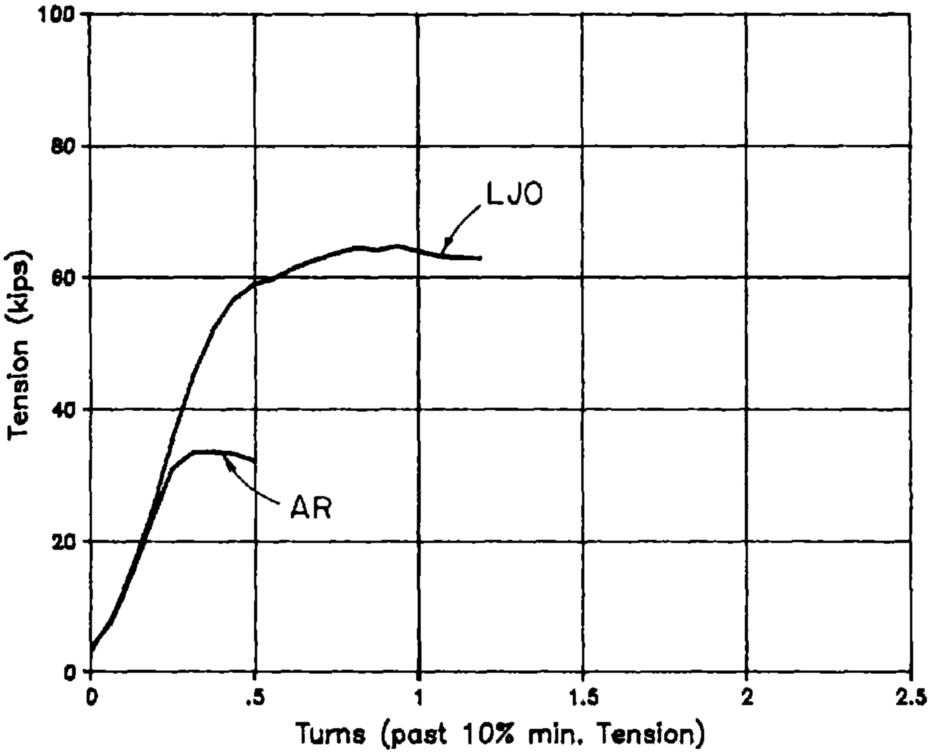


Figure 43. G assembly results (A490-B).



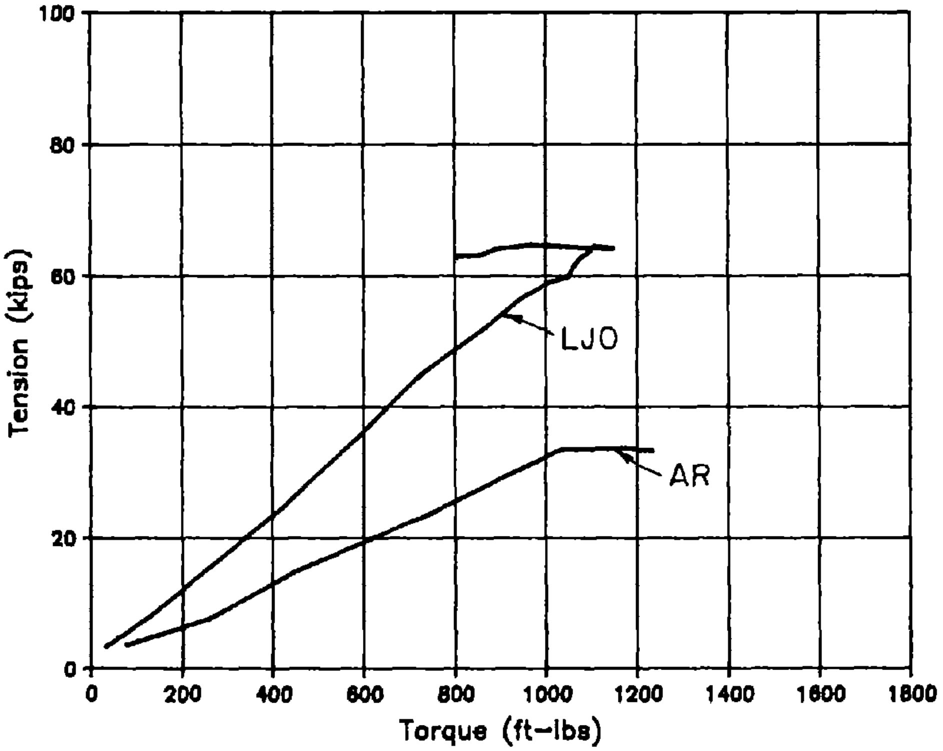


Figure 44. K bolts (HG) with R nuts (MG) results.

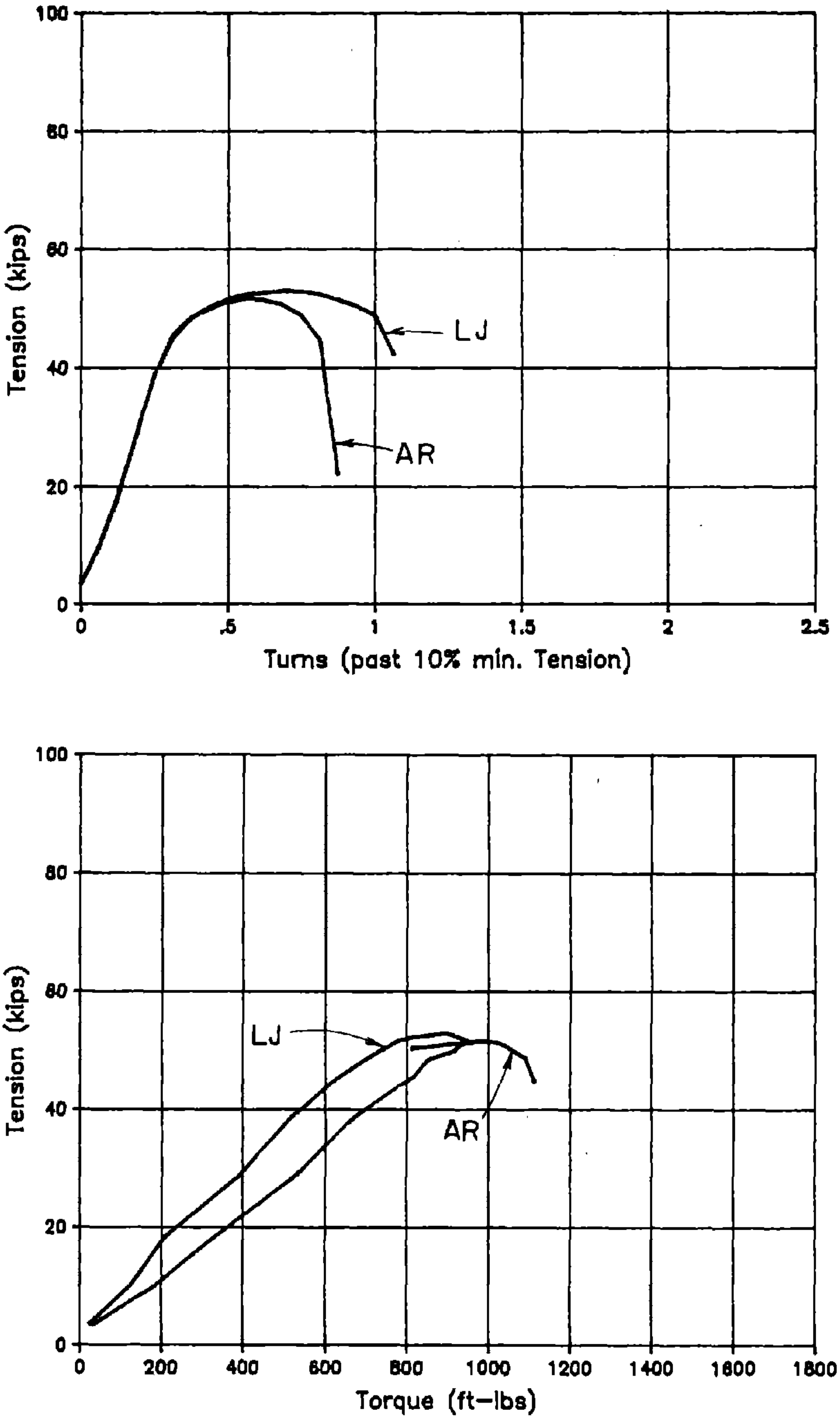


Figure 45. I bolts (HG) with D nuts (MG) results.

Summary of Results. The results of the A325 bolt tests, both galvanized and black, are summarized using bar graphs in figures 46-48. The figures show the as-received results at the top and the lubricated results at the bottom (AR and LJ1). Figure 46 shows the torque results of the tests. The general trend of lower torque for the lubricated bolts is evident for both coated and uncoated bolts. Torque alone, however, is not necessarily a good indicator of lubrication performance. The maximum torque for a lubricated bolt may be higher than the as received bolt due to a higher tension in the bolt at the torque level. Ideally the fastener assembly should have a linear torque-tension relationship. A linear relationship allows the calibrated wrench to be used for installation and for checking bolt tension after installation.

In order to examine the torque-tension relationship of the assemblies for the two lubrication conditions the data shown in figure 46 were replotted in terms of the nut factor K. The nut factor is often used to establish torque requirements for installation and for sizing wrenches to install bolts. The nut factor is defined as:

$$K = \text{Torque}/(\text{Bolt Tension} \times \text{Bolt Diameter})$$

from equation 1. Consistent units must be used for each value. The calculated value of the nut factor is shown in figure 47. The nut factor for the as-received assemblies in the top bar graph shows considerable variation. The value of nut factor varies with the tension particularly for the D and F assemblies. The range for all the bolts is between 0.08 to 0.52. The lubricated bolts in the lower bar graph show much less variation. The nut factor does not vary much for a particular bolt. The F bolt shows the largest variation. The value among all the bolts is reasonably constant. The average value is approximately 0.15. This is lower than the average value often used of 0.20 for normally lubricated black bolts. The data indicates that properly lubricated bolts can provide consistent torque-tension behavior. Also galvanized bolts when assembled with properly lubricated nuts can attain torque-tension behavior similar to black bolts.

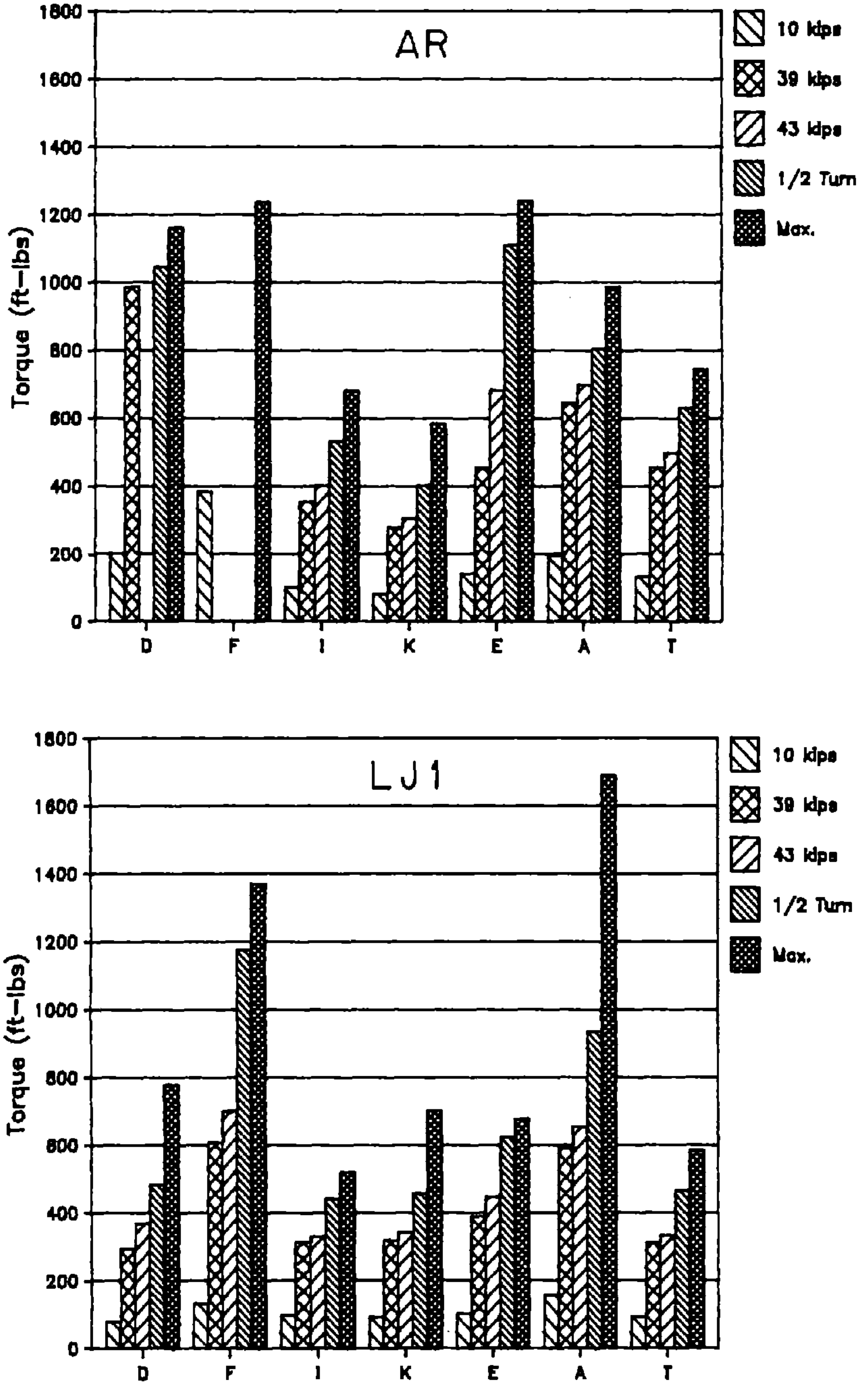


Figure 46. Torque summary of A325 tests.

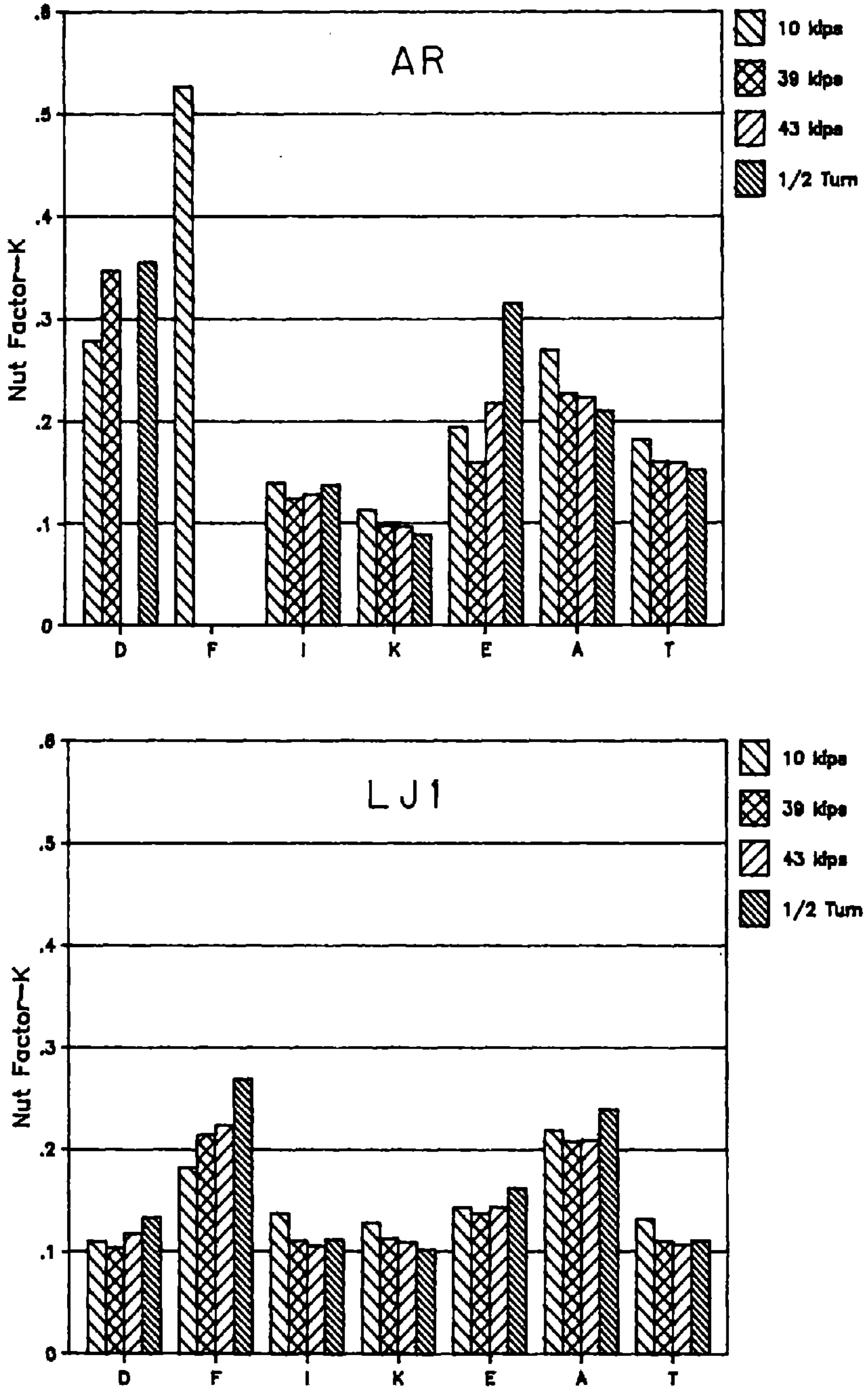
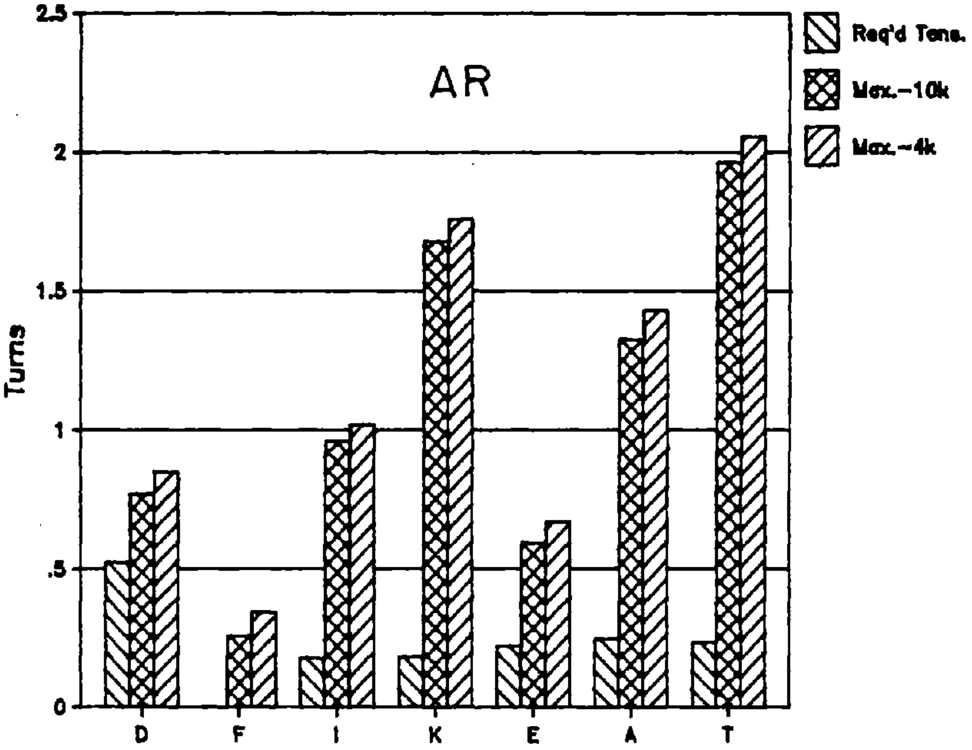


Figure 47. Nut factor for A325 bolts.



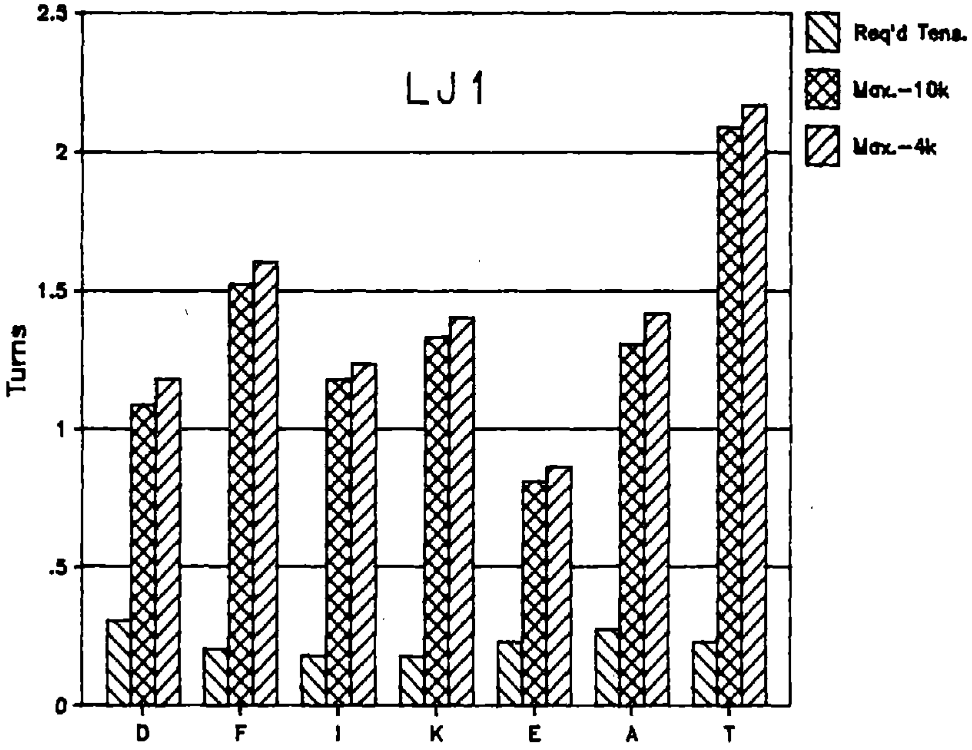


Figure 48. Turn results for A325 bolts.

Figure 48 shows the influence of lubrication on bolt ductility. The increase in the bolt ductility as measured using the turns to failure is quite evident. The turns to failure are shown using both a 4 and 10 kip (18 and 44 kN) starting point. All bolts, except the E assemblies, reached the ASTM required rotation of one turn when lubricated. The turns to the required tension was reduced when the bolts were lubricated. The apparent reduced ductility for lubricated K assemblies compared to the as-received condition is not really valid as shown in figure 36. The grater number of turns for AR was accompanied by a great reduction in bolt tension.

Discussion of Torqued-Tension Tests

The torqued-tension test setup used was representative of solid plate connections. Therefore, those bolts that reached at least one turn past snug, which in this case was defined as 10 percent of the required pretension, without a reduction in strength of more than 10 percent of the maximum tension reached were said to have performed satisfactorily.

In summary, 83 percent of the A325 black bolts tested performed satisfactorily. The remaining 17 percent involved bolts and nuts from Lots A and H where the threads had been cleaned with acetone prior to testing - a surface condition which is not representative of those encountered in common practice. The loading in those particular bolts had to be terminated because of the limited capacity of the torque wrench used. The torques in this case were reaching values over 1200 ft-lbs. (1600 N-m). As discussed earlier in this report, the limiting capacity of the commonly used torque wrenches was one of the main reasons for establishing a torque limit for satisfactory performance of bolts. Based, therefore, on the criteria for good performance, the cleaned A325 black bolts from the A and H lots were considered unsatisfactory. Since no turn tests on flat plates were conducted on A325 black bolts with the same surface condition, it was not possible to predetermine the performance characteristics of these bolts.

This was not the case, however, with A325 hot-dip galvanized bolts, most of which (89 percent of bolts tested) failed the turn test on flat plates. The bolts from one of the lots (C) that exhibited a high rate of stripping failures during the turn tests on flat plates (100 percent), as well as during the direct tension tests (100 percent), were not tested in torqued-tension, and, therefore, no values are listed for this Lot in table 5. Thus, these results would render the performance of the C bolts unsatisfactory. The poor performance of the other hot-dip galvanized A325 bolts tested with flat plates, was also confirmed through the torqued-tension tests. Fifty percent of the E bolts, never reached the one turn past snug, mainly due to high torque values required to reach the one turn limit. All the as-received and cleaned bolts, as well as some of the lubricated bolts failed to reach one turn. Only certain types of lubricants, namely, MacDermid, Anti-seize, wax and molybdenum were effective in reducing the high torque values which allowed the bolt to go through at least one turn of the nut. The bolts in the third lot of hot dipped galvanized bolts, I, barely made it to one turn past snug. The bolts of the fourth lot, K, whose tensile strength was unusually high (158 ksi, 1090 MPa) performed satisfactorily and failed by stripping after the one turn. In summary, the performance of hot dipped galvanized bolts was satisfactory only after the bolts were lubricated.

The problem of high torque values was also encountered in the testing of mechanically galvanized A325 bolts. Two lots of bolts and nuts tested (D and F) exhibited identical behavior, reaching torques close to or exceeding 1200 ft-lbs. (1600 N-m) before the tests were terminated. All of the bolts tested in the as-received state, cleaned and weathered conditions, failed to reach one turn in the torqued-tension tests. In some cases this was due to termination of loading to avoid damage to the torque load cell. Only when lubricated did these bolts reach or exceed the one turn but the required torque to reach this limit was still unacceptably high in some cases. While the flat plate tests clearly indicated that there might be a problem with the D bolts (3 and 4 both tested did not reach one turn) the F bolts showed no evidence of such a problem except that very high torques were required to turn the nut through the required 360 degrees. In two of the bolts, torques close to 1500 ft-lb (2000 N-m) were required. It is, thus, questionable whether such a performance can be viewed as satisfactory under these conditions. As with the hot-dipped galvanized bolts, mechanically galvanized bolts must also be lubricated for ensuring proper installation and satisfactory performance.

In addition to A325 bolts, four lots of A490 bolts were also tested. One single observation that characterized the performance of these bolts was the high torques required to reach the maximum tension and to go through the one turn test. Of the 43 bolts tested, ten bolts tested failed to reach one turn. Of these, nine were cleaned with acetone before testing - a surface condition which is not practical. Thus, apart from the fact that high torque values were required to reach the one turn beyond snug, in general the A490 bolts performed satisfactorily

A number of tests were also conducted on mixed bolts and nuts, mainly to evaluate the stripping performance of some of the bolts. The results from these tests will be discussed later in this section.

Solid Plate Tests

The bolts used in the current experimental program were tested to check their rotational capacity when installed on solid plates. The criterion for satisfactory performance in those tests was whether the bolts could reach a specified rotation without failure. The values chosen for maximum rotation were those currently specified in the ASTM A325 Standard; namely, 300 degrees for bolts up to 4-in long (102 mm) and 360 degrees for both over 4-in (102 mm) long. The results are given in table 7. A total of 64 bolts were tested on solid plates. Bolts from each of five categories, namely black A325, black A490, hot-dip galvanized A325, mechanically galvanized A325, and mixed bolts and nuts, were tested. The number of bolts in each category, as well as the number of bolts that failed to reach the required rotations, is also shown in this table. Of the six A325 black bolts that were tested, only one failed to reach the required turn limit, indicating satisfactory performance. Only as-received bolts were tested in this case - a practice which is representative

Table 7. Solid plate tests[1]

		Surface Conditions			
Bolt Lot	Nut Lot	AR	C	L	Bolt Type[2]
A	A	1/3[3]	---	---	A325B
H	H	0/3	---	---	"
T	T	---	---	---	"
B	B	0/3	---	---	A490B
G	G	0/2	---	---	"
L	L	1/3	---	---	"
J	J	0/2	---	---	"
C	C	2/2	2/2	2/2	A325HG
E	E	3/3	---	3/3	"
I	I	2/3	---	---	"
K	K	2/3	---	---	"
D	D	---	2/2	1/2	A325MG
F	F	0/3	---	0/3	"
A	C	0/3	---	---	A325B
A	D	0/3	---	---	"
C	A	0/3	---	---	A325G
C	P	---	0/2	0/2	"
C	Q	---	---	1/2	"
C	Q	---	0/2	---	"
D	A	0/3	---	---	A325MG

---

[1] A torque wrench was used to tighten the bolts.

[2] In the Bolt Type designation B stands for black, HG for hot galvanized and MG for mechanically galvanized

[3] 1 out of 3 bolts tested failed the test.

of what would be expected in actual field conditions. Had the bolts in this case failed the turn test, alternative surface conditions such as appropriate lubrication would have been recommended.

A similar satisfactory performance was observed in the A490 black bolts where only one of the ten bolts tested in the as-received condition failed. This was not the case, however, with the galvanized bolts where 16 of the 18 hot-dip galvanized A325 bolts and three of the ten mechanically galvanized bolts tested failed to reach the turn limit. Some of the bolts passed the solid plate turn test yet failed to reach one turn in the torqued-tension tests. This was possible because the torque limit on the wrench used in the solid plate test was much larger than the limit on the electronic load cell. Also, the solid plate stiffness was slightly less than the stiffness of the load cell in the torqued-tension test setup as discussed in chapter 3.

There are two main factors that contributed to the failure of these bolts to reach the turn limit: high friction resistance developed between the bolts and the nuts requiring excessive torques to turn the nuts and thread stripping of the bolts. The performance of these bolts was representative of that observed in the torqued-tension tests which will be discussed below.

A number of bolts were also tested using nuts from different lots, mainly to evaluate the stripping performance of these bolts. The results from testing these mixed bolts and nuts were valuable in establishing interface tolerances for preventing stripping failures and demonstrating the importance of matched bolt-nut assemblies.

Stripping Performance

A considerable amount of discussion in this report has been devoted to stripping of the bolts and the importance of ensuring adequate design against this mode of failure. This section of the report will focus on the experimental results involving stripping failures and an evaluation of the performance of the various types of bolts tested will be made through comparison with Alexander's model. A list of all stripping failures of the bolts tested under both direct tension and torqued tension is given in table 8. These are listed in the order of possible stripping as predicted by Alexander. The values of (T_{strip}/T_u) shown indicate whether stripping will occur. The higher the ratio, the smaller the probability of stripping. Of the 385 bolts tested, 63 bolts, or 16 percent, failed through stripping. Fifty-one of these bolts that stripped, or 81 percent, were galvanized bolts. A summary of striping failures according to surface conditions and type of bolts is given in table 9. While 22 percent of the bolts tested in the as-received condition failed by stripping, this number was reduced to 11% when the bolts were lubricated. A more detailed discussion of the results for each of the types of bolts tested is given below.

A325-black bolts. A total of 72 bolts from three different manufacturers were tested under both tension and torqued tension load. Various surface conditions were investigated, including clean and lubricated conditions, in order to obtain performance characteristics and determine the failure mode of these bolts. Of these, five bolts failed through nut stripping: three under direct tension and two under torqued tension. The three bolts that stripped under direct tension were intentionally installed with the bolt receded in the nut by two threads in two of the tests and three threads in the other test. The fourth stripping failure occurred after considerable necking of the bolt under torque-tension and after the bolt had undergone two turns of the nut. Similarly, the fifth bolt which had been cleaned and lubricated with a solution of one part Jon Cote 639 and one part water, stripped after two turns of the nut. Under the criteria established earlier the performance of these two bolts is satisfactory.

A325-hot-dip galvanized bolts. A total of 145 hot-dip galvanized bolts from four different manufacturers were tested. Of these 45 failed through stripping, almost all of the bolts that stripped came from two of the four manufacturers [31 stripping failures out of 31 bolts tested from one manufacturer (C) and 13 stripping failures out of 19 bolts from another manufacturer (K)]. Various surface conditions were investigated in these

Table 8. Stripping failures of high strength bolts.

Bolt Lot	Nut Lot	Bolt Type	$(\frac{T_{strip}}{T_u})$ Theory	Direct Tension AR	Direct Tension C	Direct Tension L	Direct Tension W	Direct Tension HCL-LJT	Torqued Tension AR	Torqued Tension C	Torqued Tension L	Torqued Tension W	Torqued Tension HCL-LJT	Total
A	C	A325B	1.003	—	—	—	—	—	0/3	—	—	—	—	0/3
C	C	A325HG	1.007	12/12^4	2/2	3/3	—	—	10/10	2/2	2/2	—	—	31/31
D	D	A325MG	1.033	1/3	1/3	0/2	—	—	0/3	0/5	0/34	0/3	—	2/53
I	D	A325HG	1.085	—	—	—	—	—	0/3	—	0/3	—	—	0/6
A	D	A325B	1.102	—	—	—	—	—	0/3	—	—	—	—	0/3
E	E	A325HG	1.109	0/2	—	—	—	—	0/8	0/3	0/22	—	—	0/35
K	K	A325HG	1.207	0/3	—	—	—	—	3/4	3/3	2/3	2/3	3/3	13/19
B	B	A490B	1.249	5^3/9	0/2	0/2	—	—	0/11	0/3	1/3	0/3	—	6/33
F	F	A325MG	1.262	0/3	—	—	—	—	0/9	0/3	4/9^2	0/3	—	4/27
T	T	A325B	1.343	0/1	—	—	—	—	0/4	0/3	1^2/3	1^2/3	—	2/14
I	I	A325HG	1.378	0/3	—	—	—	—	0/6	0/3	0/3	0/3	0/3	0/21
D	A	A325MG	1.469	0/2	—	—	—	—	0/3	—	—	—	—	0/5
G	G	A490B	1.478	0/3	0/2	0/2	—	—	0/6	0/3	0/10	0/3	—	0/29
A	A	A325B	1.509	3^3/12	0/2	0/2	—	—	0/7	0/3	0/3	0/3	—	3/32
J	J	A490B	1.522	0/2	—	—	—	—	0/3	—	1/3	—	—	1/8
K	G	A325HG	1.527	—	—	—	—	—	—	—	—	—	0/3	0/3
L	L	A490B	1.529	—	—	—	—	—	0/4	0/3	0/3	0/3	—	0/13
C	A	A325HG	1.530	—	—	—	—	—	0/3	—	—	—	—	0/3
C	Q	A325HG	1.567	0/1	0/2	0/2	—	—	—	0/2	1^2/2	—	—	1/9
K	R	A325HG	1.588	—	—	—	—	—	0/3	—	0/3	—	0/3	0/9
C	R	A325HG	1.629	—	—	—	—	—	—	—	0/1	—	—	0/1
C	P	A325HG	1.674	—	0/2	0/2	—	—	—	0/2	0/2	—	—	0/8
H	H	A325B	1.706	0/2	0/2	0/2	—	—	0/5	0/3	0/3	0/3	—	0/20

[1] Bolt end flush with the nut
[2] Stripped after 1 turn
[3] With 1, 2 or 3 threads receded in the nut
[4] Number of bolts stripped/number of bolts tested

Table 9. Summary of stripping failures

SURFACE CONDITION	DIRECT TENSION A325B	A325HG	A325MG	A490	TORQUED TENSION A325B	A325HG	A325MG	A490	TOTAL
AR	3/15[1]	12/21	1/8	5/14	0/22	13/37	0/15	0/24	34/156
C	0/4	2/6	1/3	0/4	0/9	5/15	0/8	0/9	8/58
L	0/4	3/7	0/2	0/4	1/9[2]	5/41	4/43	2/19	15/129
W	—	—	—	—	1/9[2]	2/6	0/6	0/9	3/30
HCL-LJ1	—	—	—	—	—	3/12	—	—	3/12
TOTAL	3/23	17/34	2/13	5/22	2/49	28/111	4/72	2/61	63/385

[1] 3 stripping failures in 14 bolts tested

[2] Stripping in these bolts occurred after one turn of the nut

series of tests. The variables that could ultimately dictate the mode of failure for the four lots of bolts: interface clearance, hardness of the nuts, and thread length.

Table 10. Physical and mechanical characteristics of A325 (HG) bolts.

	Lot C	Lot K*	Lot E	Lot I
	(Failure by Stripping)		(Failure by Fracture)	
Interface W/O Zn (in)	0.053	0.061	0.060	0.072
Nut R_c	26	32	27	31
Thread length (in)	1.53	1.41	1.56	1.56

(1 in = 25.4 mm)
*It should be pointed out that three of the K bolts that stripped were recorded as "almost" stripped upon closer examination.

In 12 of the bolts tested under torqued tension the zinc was removed with hydrochloric acid and were then lubricated. Three of these bolts failed through stripping. These three bolts were from the same lot as those bolts that had shown a high stripping rate (lot K) with the zinc present. Three bolts whose zinc was removed but did not strip came from lot I. None of the bolts in that lot had stripped with the zinc present. Six bolts from the K lot were also tested, after the zinc was removed, with nuts from other lots. These did not strip. Based on the parameters shown in table 10, it appears that low interface values and low nut hardness maybe the primary contributing causes to the stripping failures observed. Although a high number of such failures took place in the bolts of lot K, stripping did not actually occur until after at least one turn of the nut - a condition which would render their performance satisfactory.

A325-mechanically galvanized bolts. A total of 85 mechanically galvanized bolts were tested under direct tension and torqued tension. These bolts were obtained from two different manufacturers. Of all the bolts tested, six failed through stripping. Two bolts (out of 53 tested) were from one manufacturer (D) and failed in the as-received and clean condition under direct tension. The as-received bolt was installed with the bolt end flush with the nut. The remaining four bolts that failed through stripping were from the second manufacturer (F). Three of these failures involved bolts that were initially cleaned and then lubricated with a solution of one part Jon Cote 639 and one part water. The other bolt that failed had been lubricated with an antiseize lubricant. These stripping failures occurred in bolts tested under torqued tension after a rotation of the nut of over 1.5 turns. According to the performance criteria established earlier in this report, the performance of the lubricated F bolts could be considered satisfactory since no failure occurred before one turn of the nut.

The interface, nut hardness and thread length of the bolts tested are listed below:

Table 11. Physical and mechanical characteristics of A325 (MG) bolts.

	Lot D	Lot F
Interface (in)	0.045	0.072
Nut R_c	31	28
Thread length (in)	1.62	1.44

(1 in = 25.4 mm)

A490-black bolts. A total of 83 bolts from four different manufacturers were tested under direct tension and torqued-tension. Various surface conditions were also investigated. Only seven bolts failed through stripping. Of these, three bolts were installed with two threads receded in the nut and two bolts were installed with one thread receded in the nut. The other two bolts that stripped had been previously cleaned and then lubricated, one with a solution of one part Jon Cote 639 and one part water, and the other with MacDermid. This last bolt was 1 in (25 mm) in diameter.

Mixed bolts and nuts. A total of 50 bolts were tested with non-matching nuts under both tension and torque tension loading. There was only one stripping failure.

A theoretical model for evaluating the stripping load of a threaded system (bolt, nut) was discussed in chapter 2 of this report. It was shown that given the physical and mechanical properties of the threaded system a stripping-to-tension strength ratio may be computed. A ratio less than 1.0 would indicate failure through stripping and a ratio greater than 1.0 would indicate failure of the bolt through fracture. The stripping-to-tension strength ratios of all the bolt-nut combinations tested were computed and are given in table 8 and are also shown graphically in figure 49 as a function of the depth of thread engagement of the bolt and the nut. Shown in figure 49 are also the theoretical values for a threaded system consisting of a 2H nut and a 7/8-in (22 mm) A325 bolt. The theoretical stripping-to-tension strength ratios of both the bolt and the nut are given and, as indicated, the stripping strength of the bolt governs throughout the range of depth of thread engagement. The variation in the experimental data shown in figure 49 is due to differences in nut and bolt strengths for the individual specimens tested. Minimum nut and bolt strengths were assumed in developing the theoretical curves. Two sets of experimental data are shown: data corresponding to stripping failures that occurred before one complete turn of the nut passed snug and data corresponding to failures that occurred pass one turn of the nut. These failures include both stripping and fracture. As shown in figure 49, the theoretical model did not predict any stripping failures (no values are less than 1.0). However, the theoretical model was not developed for the range of depth of thread engagement measured in the bolt-nut systems tested. Thus, any projection of the theoretical model beyond the range for which it was developed may result in very unconservative values of stripping-to-tension strength ratios. This was discussed in more detail in chapter 2.

It is also interesting to note that a number of bolt-nut systems, including the two lots that failed through stripping, had a depth-of-thread engagement outside the permissible range of 0.06 in (1.52 mm) which takes into account the recommended overtapping value of 0.020 in (0.50 mm). Based on the results shown in figure 49, it would appear that a stricter value of overtapping would reduce the possibility of stripping. The theoretical model can still be used but with a slight modification to account for the discrepancy in the results at low values of depth-of-thread engagement.

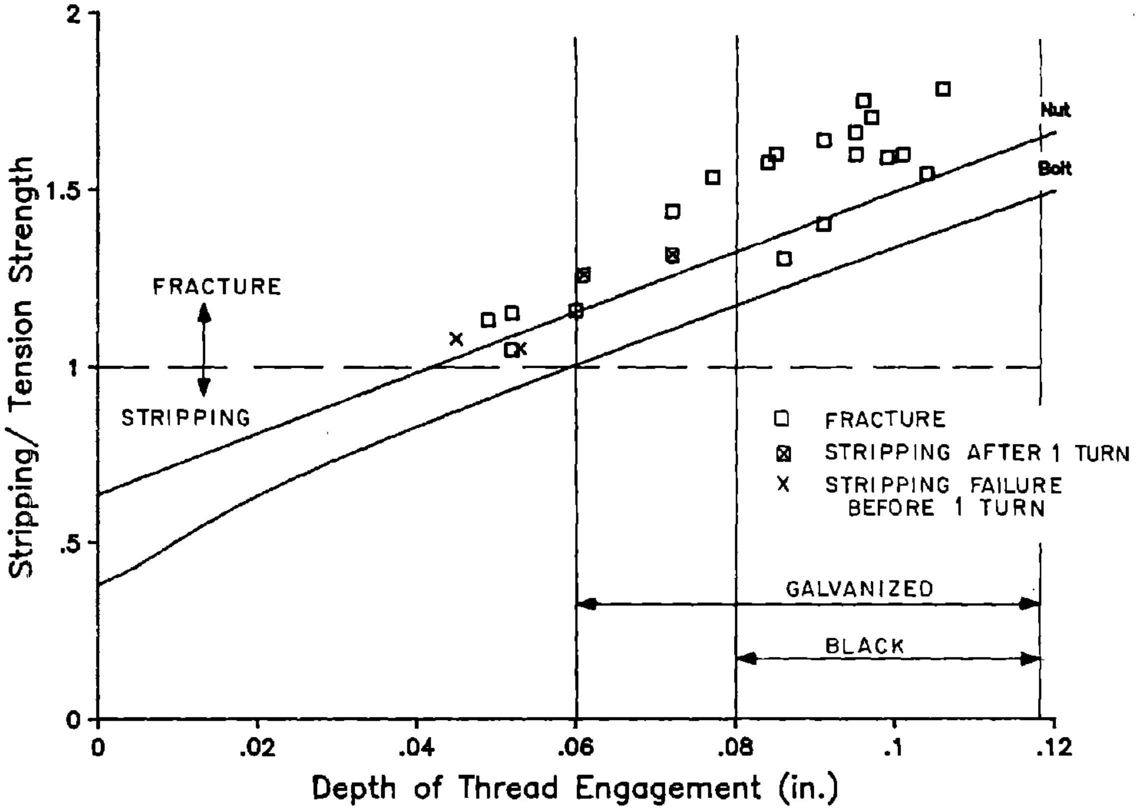


Figure 49. Comparison of tests with theoretical stripping model.

CHAPTER 5. FIELD TESTS

Bolts from a constructed highway bridge were removed in order to determine the tightness of the installed bolts and to provide additional data from bolts used in actual construction. The sponsor located the bridge containing the bolts to be investigated. The bridge selected by the sponsor was the twin girder Rehobeth Avenue Bridge in Rehobeth Beach, Delaware. The bridge had both galvanized A325 bolts and black A490 bolts. According to the records of the original contractor, the original bolts were installed by the turn-of-nut method using 1/3 turn.

The removal of the bolts and the installation of the new bolts was undertaken by the subcontractor Raymond Engineering. Photos of two of the joints are shown in figure 50. Joint #1 had galvanized A325 bolts and Joint #3 was a web splice with A490 bolts. The torque to remove the bolts was recorded. The length of the bolts was measured before and after removal. The bolt length was measured using an ultrasonic bolt gage similar to the equipment used in the laboratory. The bolts removed from the bridge were identified by a number painted on the bolt head. The bolts, nuts, and washers removed from the bridge were shipped back to the University for laboratory evaluation. A new bolt supplied by the University was installed into the joint after each bolt was removed. New nuts and washers were used to install the bolt. The elongation of the new bolts before and after installation was measured. The maximum installation torque was also recorded. The replacement bolts were installed using the turn of the nut method of installation. The bolts were snugged to a torque of approximately 200 ft-lbs and then 1/3 of a turn rotation applied to the nut. A sample of the bolts supplied by the University to replace the bolts removed were tested in the tension-torque test setup prior to shipping the bolts to Raymond. The bolts used were bought on the open market and included bolts which were part of the lubrication and stripping research study.

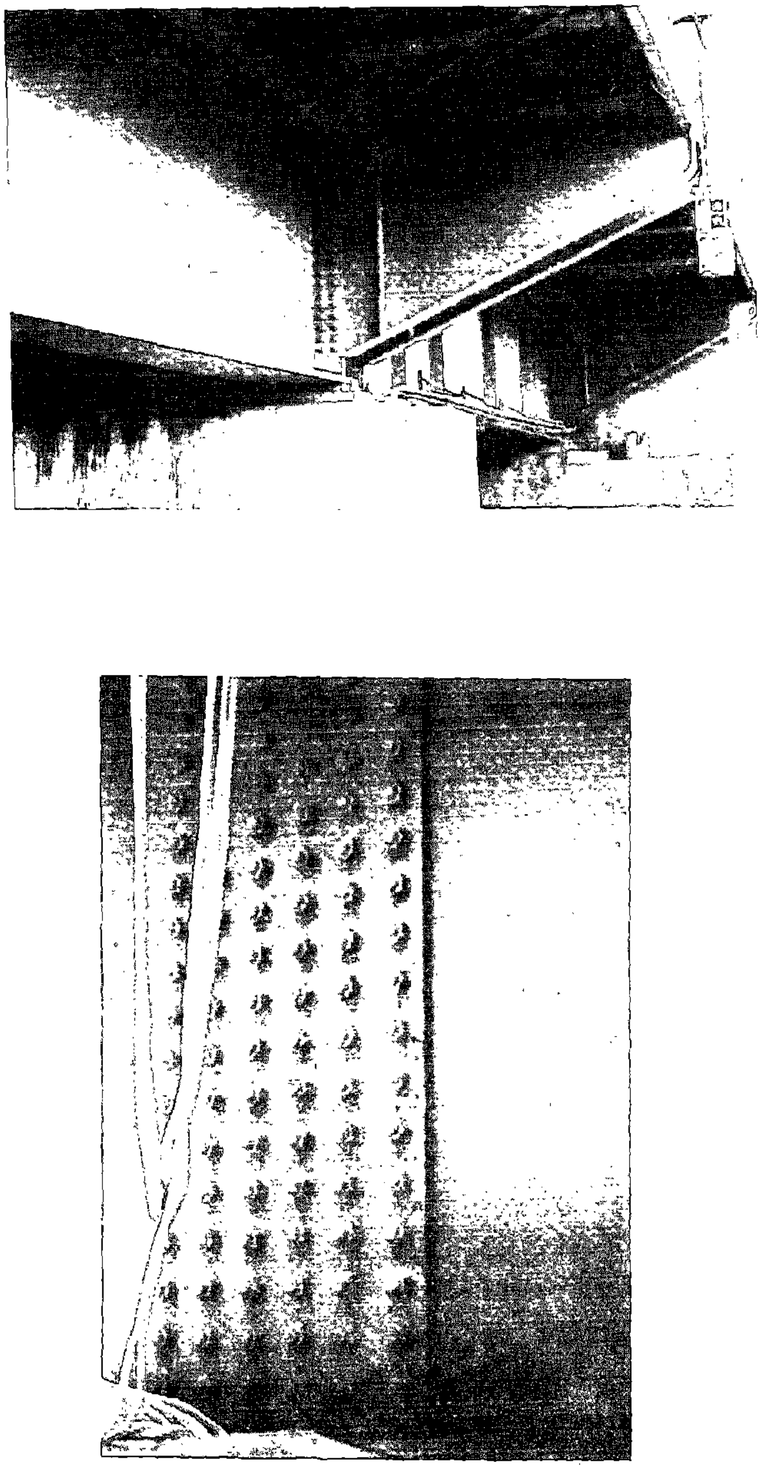


Figure 50. Connections used in field test.

A325 Galvanized Bolts

Two sets of 7/8 in (22 mm) A325 galvanized bolts were removed from the bridge. The bolts were from two different floor beam cantilever-to-girder web connections. The two sets of bolts had slightly different lengths. The bolts supplied to replace the bolts removed were the same length for both connections. The results of the study of these two joints is given below.

Joint 1. The first joint sampled had 3-1/4 in (83 mm) long bolts with a grip of 1-7/8 in(48 mm). The measured bolt stretch and removal torque for the six bolts removed from this joint are shown at the top of table 12. The bolt stretch is the difference between the bolt length before and after removal from the joint. The average bolt stretch was 6.4 mils (0.16 mm) and the average torque was 591 ft-lbs (801 N-m).

Figure 51 shows the results of the laboratory tests on bolts labeled number 2 and 6 from joint 1. The bolts were randomly selected from the six bolts removed. The bolts were calibrated in the torque-tension-turns test setup described in chapter 3. The bolt elongations were measured ultrasonically with a Raymond Bolt Gage. The top of the figure shows the tension-elongation relationship and the lower figure shows the tension-torque relationship for these two bolts. Each bolt was loaded through two tightening cycles. During the first cycle the maximum bolt tension was limited to 40 kips (178 kN) to remain in the elastic range of the bolt. The bolt was then untightened to 10 kips (44 kN) and then retightened to a load above 40 kips (178 kN). The bolt was then loosened to determine the amount of inelastic stretch in the bolt. Tension tests on bolts numbered 4 and 5 gave an average tensile load of 65.2 kips (290 kN) which corresponds to a tensile strength of 141 ksi (973 MPa). Black 2H nuts were used to establish the tensile strength by bolt fracture because bolt stripping occurred when the original overtapped galvanized nuts were used in the tension test of bolt number 3. The bolt stripping load was 64.3 kips (286 kN) which is close to the tensile fracture capacity.

Table 12. Bridge bolt removal data

Joint 1-A325 7/8-in. dia. galvanized bolts - 1.875 in grip

Bolt No.	Stretch x 10-3 in	Torque ft-lbs
1	-5.7	600
2	-6.3	600
3	-6.3	600
4	-6.2	420
5	-7.1	735
6	-6.6	N/A
Averages	-6.4	591

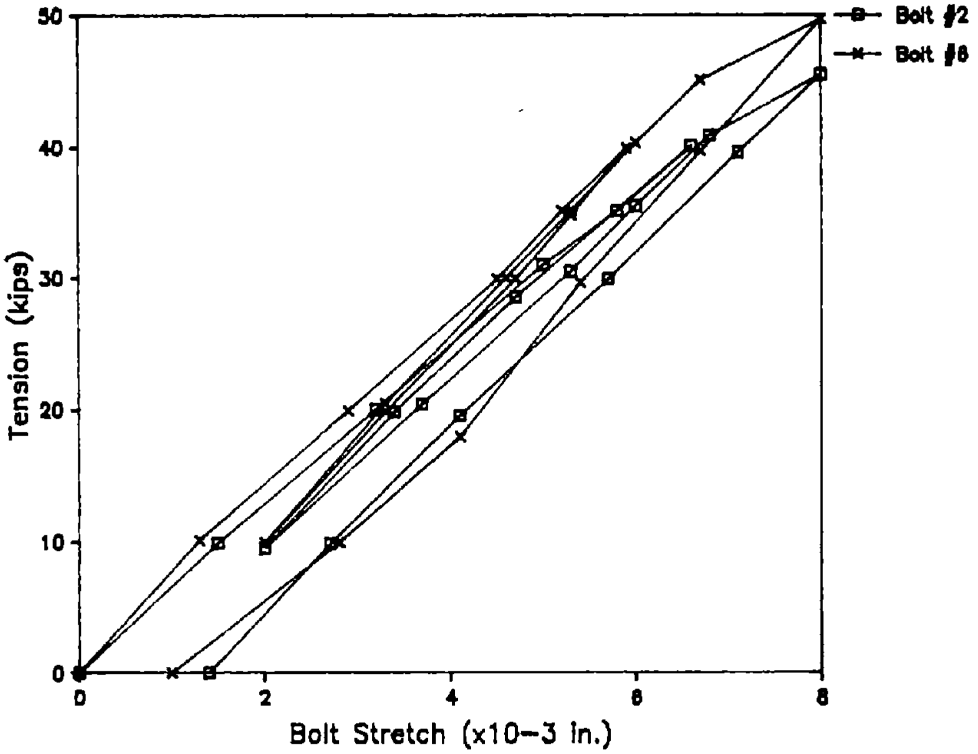
Joint 2-A325 7/8-in dia. galvanized bolts - 1.415 in grip

Bolt No.	Stretch x 10-3 in	Torque ft-lbs
7	-4.8	900
8	-5.5	450
9	-5.2	750
10	-6.4	675
11	-5.2	N/A
Averages	-5.4	694

Joint 3-A490 1 in dia. - 3.165 in grip

Bolt No.	Stretch x 10-3 in	Torque ft-lbs
1	-10.1	N/A
2	-9.5	750
3	-12.6	1050
4	-12.5	1050
5	-13.4	1200
6	-13.8	1050
7	-15.4	1050
8	-13.5	1125
9	-11.2	975
10	-9.2	1485
11	-11.4	1050
Averages	-12.1	1079

1 in = 25.4 mm; 1 ft-lb = 1.355 N-m



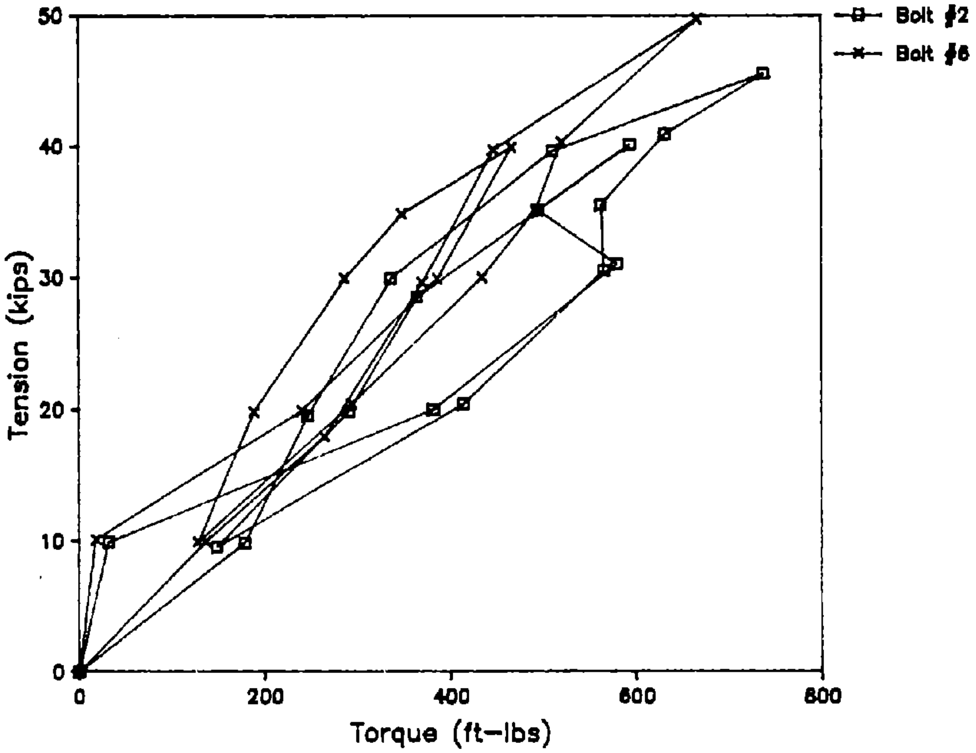


Figure 51. Test result of bolts from joint 1.

The average stretch of the bolts removed indicate that the installed bolt tension was approximately 40 kips (178 kN). This meets the specification requirement of 39 kips. The average removal torque also indicates an installed tension of approximately 40 kips (178 kN). All of the bolt stretches measured during the removal of the bolts were within the elastic range of the bolts indicating that the bolts had not been taken into the inelastic range as would be expected with the 1/3 turn-of-nut installation method used in the original installation. Perhaps the bolts in the joint had not been brought to the fully snug position before developing the required turns. The tension in the short grip bolts would be especially sensitive to the snugging operation.

Joint 2. The second joint sampled had 2-3/4 in (70 mm) bolts with a grip of 1.415 in (The measured bolt stretch and torque for these bolts is given in the middle of table 12. The average stretch of the five bolts was 5.4 mils (0.14 mm) and the average torque was 694 ft-lbs. (940 N-m). The average bolt stretch was less than in joint 1. The average torque of the bolts was larger than in joint 1. In a tension test, bolt number 8 stripped at 65.2 kips (290 kN) when the original overtapped galvanized nut was used. When black nuts from Lot P were used, bolts 9 and 11 fractured at an average load of 66.1 kips (294 kN) which gives a tensile strength of 143 ksi (986 MPa).

Figure 52 shows the results of the laboratory tests. Two bolts were tested. Bolts marked number 7 and 10. The results of the laboratory study indicate that the tension in these bolts was less then the specified tension of 39 kips (173 kN). The tension corresponding to the average elongation is 35 kips (156 kN). The range of removal torques indicates a bolt tension between 34 to 43 kips (151-191 kN). The two bolts tested in the laboratory showed different torque tension relationships at higher loads. This is not unexpected since the bolts had been previously tightened and exposed to painting and weathering. Any lubrication present on the bolts which would reduce the scatter in the results was most likely degraded due to the prior history of the bolts. Again, the low tension in the bolts may be due to inadequate snugging.

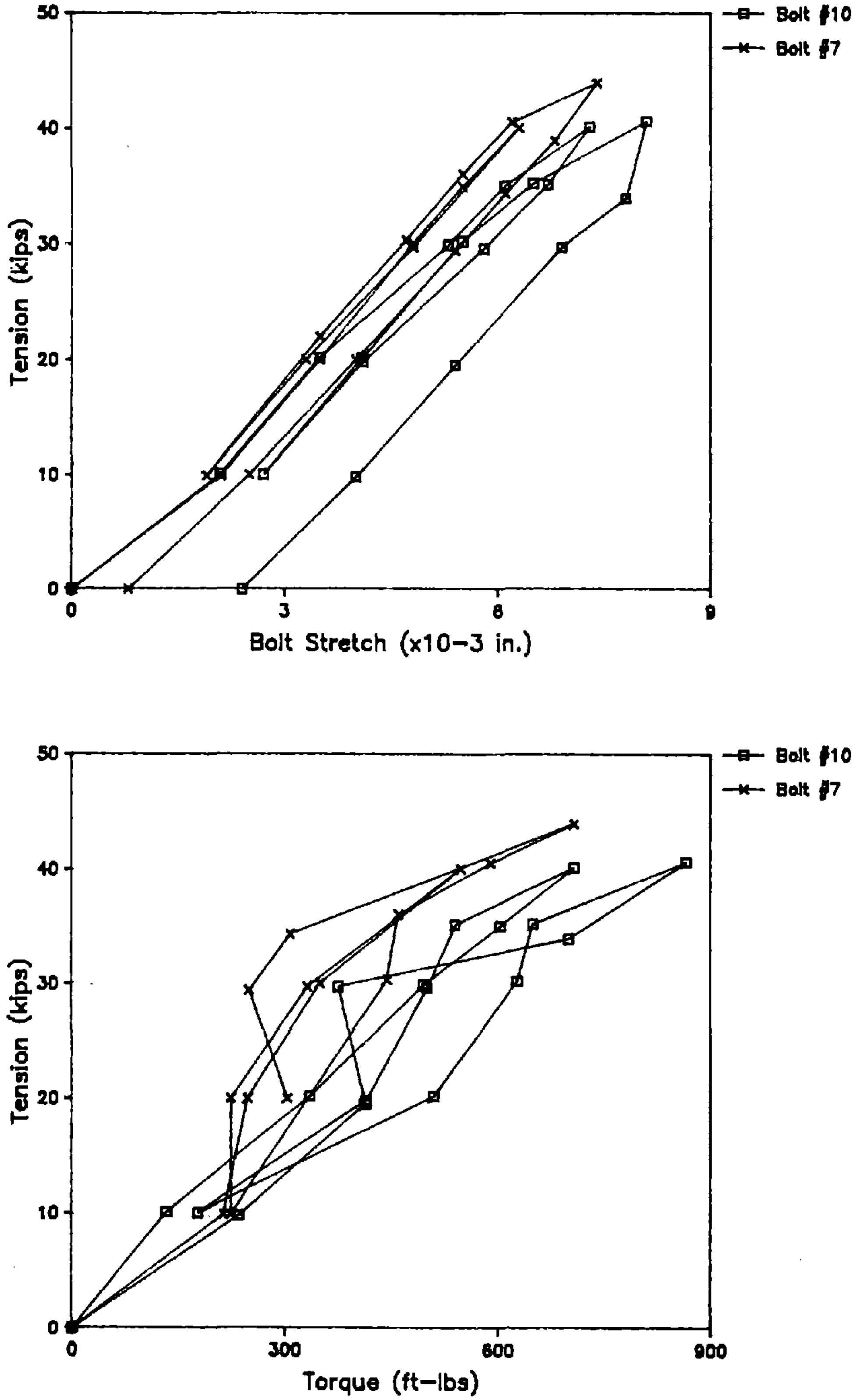


Figure 52. Test results of bolts from joint 2.

Installation of Replacement A325 Galvanized Bolts

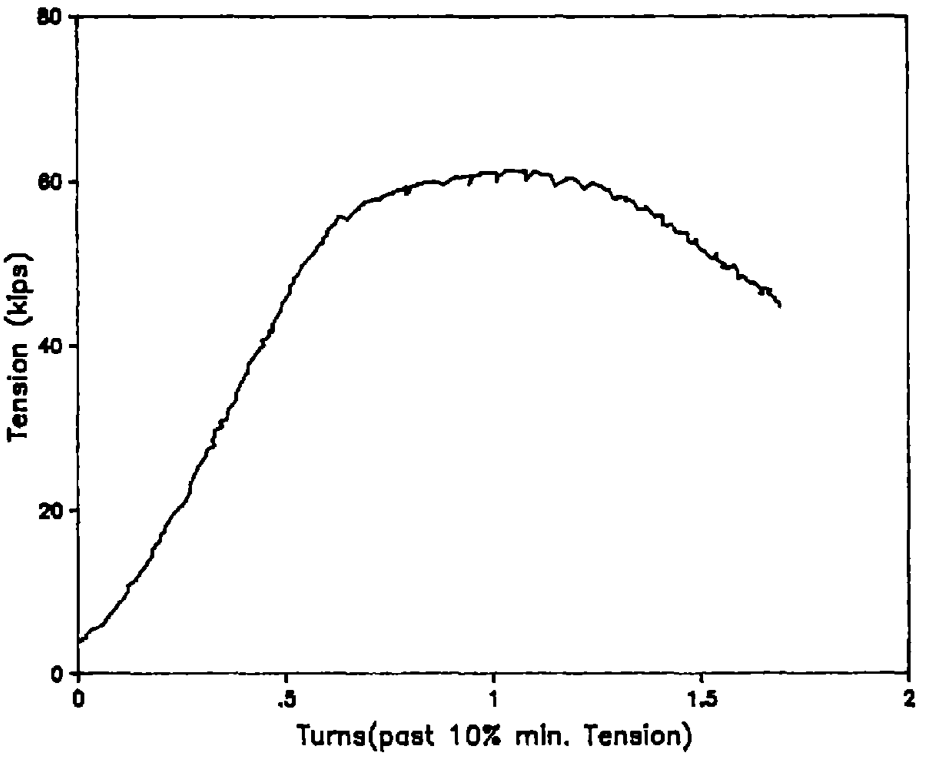
The results of the tension-torque test performed on the bolts supplied for installation on the bridge are shown in figure 53. The bolted assembly supplied had 3 in (76 mm) long hot dipped galvanized bolts from the C lot and mechanically galvanized nuts from the R lot. The nuts were lubricated with undiluted MacDermid 1186 water soluble wax. The use of these lubricated nuts with smaller overtap provided an increase in the bolt tension, decrease in the torque requirements, and an increase in the bolt ductility versus the nut supplied with the bolt by the manufacturer. The R nut also eliminated thread stripping.

The results of the field installation of the bolts are given in table 13. The installation torque range was between 375 and 600 ft-lbs (508-813 N-m). The estimated tension in the bolts based on the laboratory calibration is between 49 and 60 kips (218-267 kN). These tensions are much higher than the required value and also the values estimated for the original bolts installed in the bridge.

The high installed bolt tensions resulted from the use of the turn of the nut method of installation coupled with a ductile bolt with good strength and with no stripping. The large bolt stretch measured during the installation of the bolts indicate that the turn-of-the-nut method was properly performed. The bolt stretch measured was three times that measured from the bolts removed from the bridge. The difference in bolt stretch is probably due to difference in installation procedures. Even though the new bolts were tightened to a larger bolt stretch and a larger tension, the torque required for installation was less than the removal torques due to the efficiency of the lubrication employed.

A490 Black Bolts

The third joint sampled in the bridge contained 4-1/2 in (114 mm) long 1-in (25 mm) diameter A490 bolts. The connection was a web splice in the girder



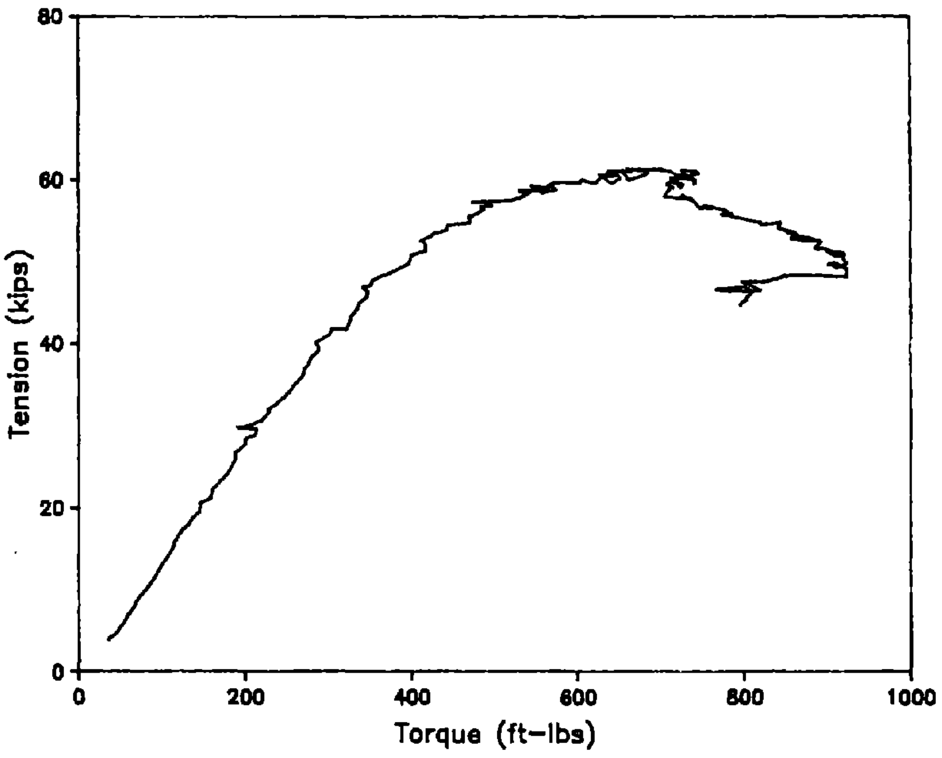


Figure 53. Tension-torque test results of galvanized replacement bolts.

Table 13. Bridge bolt installation data.

Joint 1-A325 7/8-in dia. galvanized bolts - 1-7/8 in grip

Bolt No.	Stretch x 10-3 in	Torque ft-lbs
1	20.0	600
2	19.0	427
3	21.4	570
4	21.6	420
5	22.1	435
6	20.0	405
Averages	20.7	490.4

Joint 2-A325 7/8-in dia. galvanized bolts - 1.415 in grip

Bolt No.	Stretch x 10-3 in	Torque ft-lbs
7	15.1	N/A
8	14.8	600
9	16.4	450
10	17.1	450
11	17.9	375
Averages	16.3	469

Joint 3-A490 1 in dia. - 3.165 in grip

Bolt No.	Stretch x 10-3 in	Torque ft-lbs
1	18.4	1275
2	18.7	1200
3	18.1	1245
4	16.0	1260
5	20.0	1275
6	20.0	1260
7	20.5	1245
8	20.1	1245
9	17.2	1245
10	18.3	1470
11	19.3	1350
Averages	18.8	1279

1 in = 25.4 mm; 1 ft-lb = 1.355 N-m

near an interior support. The grip of the bolts was 3.165 in (80 mm). The measured bolt stretch and torque for these bolts is given at the bottom of table 12. Eleven bolts were removed from the connection. The average stretch for these bolts was 12 mils (0.30 mm). The average torque was 1079 ft-lbs (1462 N-m). These are much larger values than the results from joints 1 and 2 as expected since these bolts are larger and stronger. The longer length of the bolts also requires a larger bolt stretch to attain the required tension. The measured tension-elongation response for two bolts taken from the bridge is shown in figure 54. A correlation between this calibration and measured stretch in the field, given at the bottom of table 12, indicates that the average bolt tension in joint 3 is 61 kips (271 kN) with a range of 46 to 77 kips (205 to 342 kN). The average recorded is slightly lower than the minimum specified preload of 64 kips (285 kN). Tension tests of the removed bolts numbered 7 and 8 with their original nuts gave an average bolt fracture load of 95.2 kips (424 kN) which corresponds to a tensile strength of 157 ksi (1080 MPa).

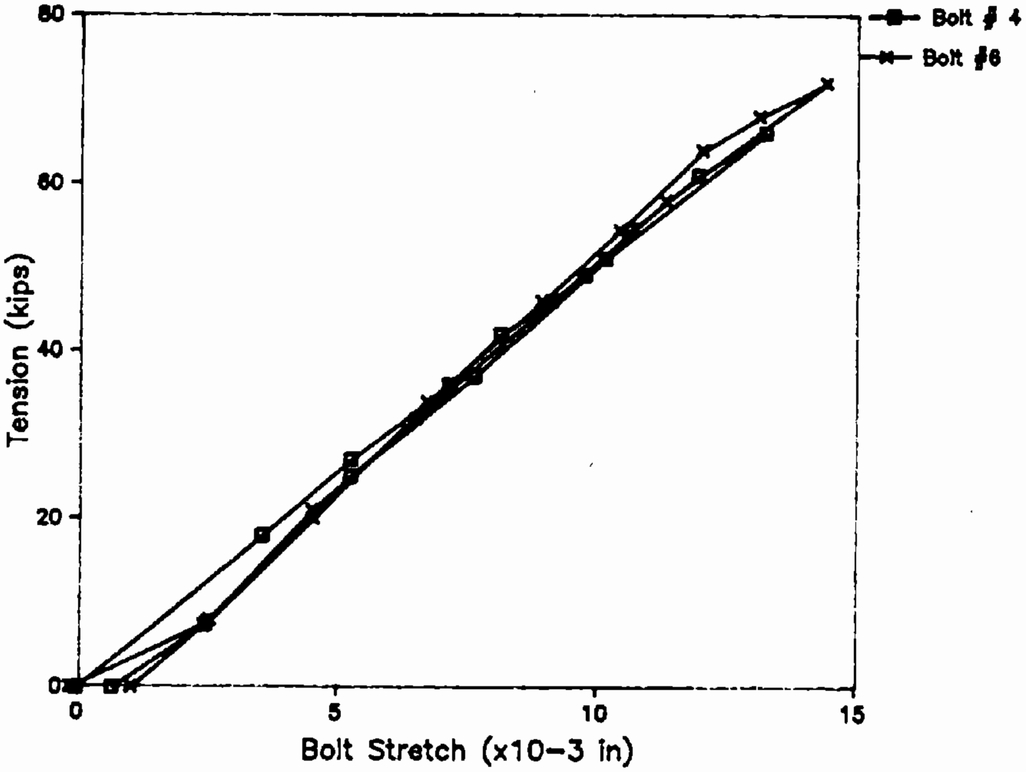


Figure 54. Calibration of A490 bridge bolts.

The results of the tension-turn test performed on the replacement bolts is shown in figure 55. The bolts, nuts, and washers are from the J lot. They were shipped to the site in the as-received condition. The nuts fit very tightly on the bolts. The nut could not be run up the threads on the bolt by hand. One bolt, which was discarded, had incomplete threads. The tight fit was of initial concern. A tension test and a solid plate turn test was performed on assemblies from this lot to determine if the tight thread fit would cause installation problems. The assemblies passed both tests without thread failure and showed good ductility in the solid plate test. The tension-turn test could not be completed to failure due to the high torque encountered in the test. The bolt was still in the elastic range at a tension of 83 kips (369 kN) and a torque of 1200 ft-lbs (1630 N-m). The bolts could not be tested further in the revised test setup which allowed higher torques due to the time schedule for the field tests. A second test using an anti-seize lubricant produced similar high torques.

The data from the field installation of the bolts is shown in the bottom of table 13. The average bolt stretch is 18.8 mils (0.471 mm) and the average torque was 1,279 ft-lbs (1733 N-m). Based on the measured installation torque the tension in the bolts exceeded 82 kips (365 kN) which exceeds the required tension of 64 kips (285 kN). The field installation of the bolts was not in strict accordance with the turn-of-the-nut method of installation. The bolt length exceeded four times the diameter. The required turn of the nut past snug is one half of a turn not the one third of a turn used. The Delaware highway department requested the 1/3 turn installation procedure for the replacement bolts in order to conform to the procedure used in the original installation. The bolts still produced the required tension with the smaller turn due to the previous compacting of the joint from the bolts installed originally.

Summary of Field Tests

The bolts removed from the bridge were installed using the 1/3 turn-of-nut method of installation. The average tension of the bolts in joint 1 was

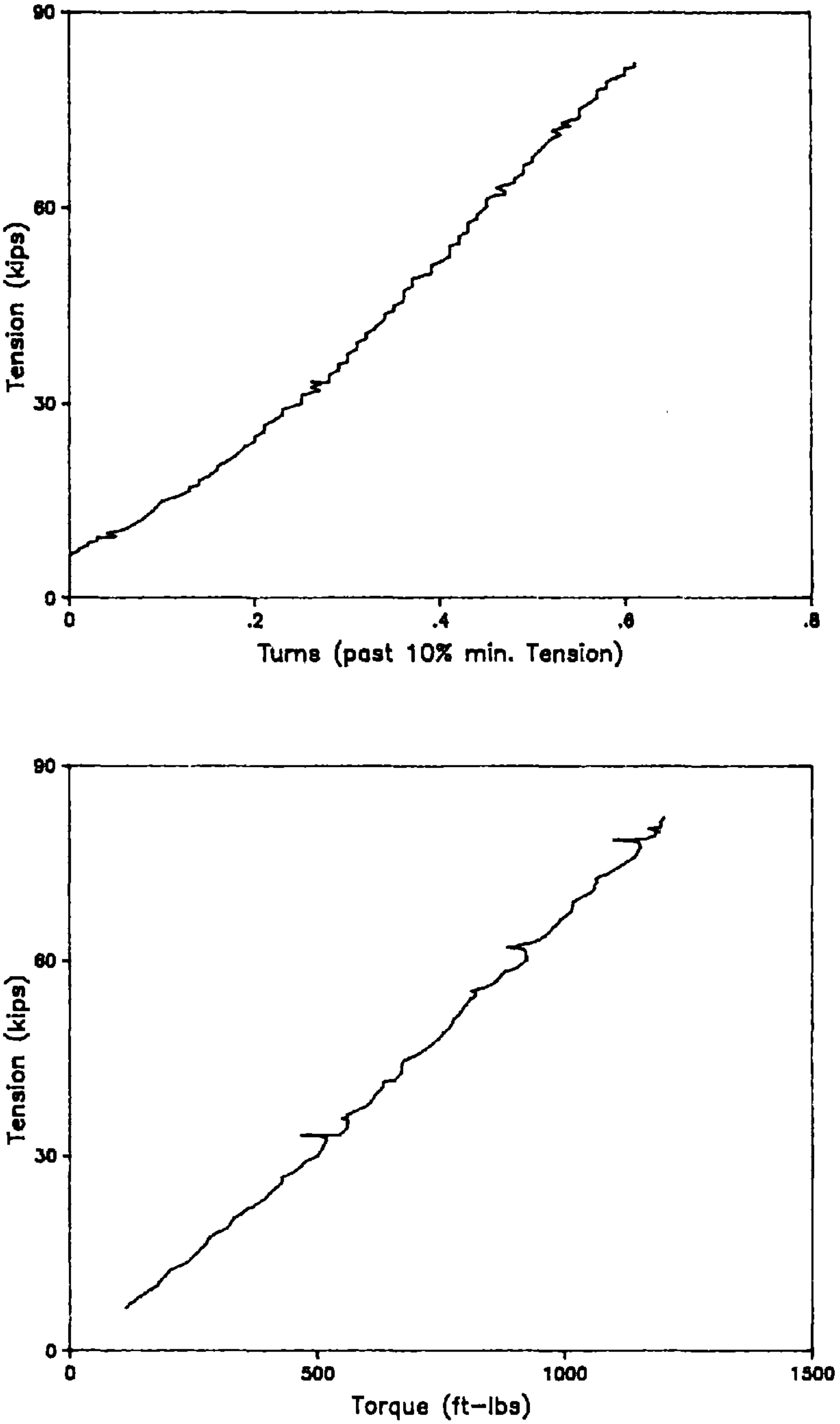


Figure 55. Tension-torque test results of A490 replacement bolts.

just at the required pretension. The average tension in the bolts of joints 2 and 3 was slightly below the required pretension. Figure 56 shows the nut factor calculated from the laboratory tests of the four galvanized bolts tested from joints 1 and 2. Although the data shows a lot of scatter, the average nut factor is about 0.20. The scatter in the data is mainly due to the inclusion of both loading and unloading data and the two cycles of tightening. The performance of these bolts which had been previously installed, painted, and exposed to the weather was better then some of the new galvanized bolts which were purchased as part of the research. The data from these tests and the field removal data indicates that good galvanized bolts are available and can be properly installed. It should also be mentioned that concern over the performance of galvanized bolts in other projects prior to the erection of the original bridge required the contractor to test the bolts. Tests were conducted at Lehigh University in a Skidmore-Wilhelm calibrator for some of the original bolts, so it is no surprise that the bolts were okay.

Figure 57 shows average torque and bolt stretch for the bolts removed and installed on the bridge. The bolt stretch of the bolts installed is obviously much larger then the bolts removed. The larger bolt stretch of the installed bolts is due to the use of a deformation control method of installation, i.e. turn of the nut. The stretch on bolt removal is limited to the elastic unloading stretch of the bolts if they are tightened into the inelastic range. The bolt stretch upon removal will always be less then or equal to the installed stretch. The data from the laboratory results indicate that the amount of stretch measured in the removal of the bolts was still less than the elastic unloading stretch. This would indicate installation by calibrated wrench. The large stretch of the installed bolts gives an indication of the need for bolt ductility when bolts are installed using the turn-of-the-nut method.

The torque required for bolt removal was comparable to the installation torques. Since the tension-torque relationships for the new bolts installed is different from the relationship for the bolts removed, the new bolts installed produced higher tensions than the bolts removed. The torques for the

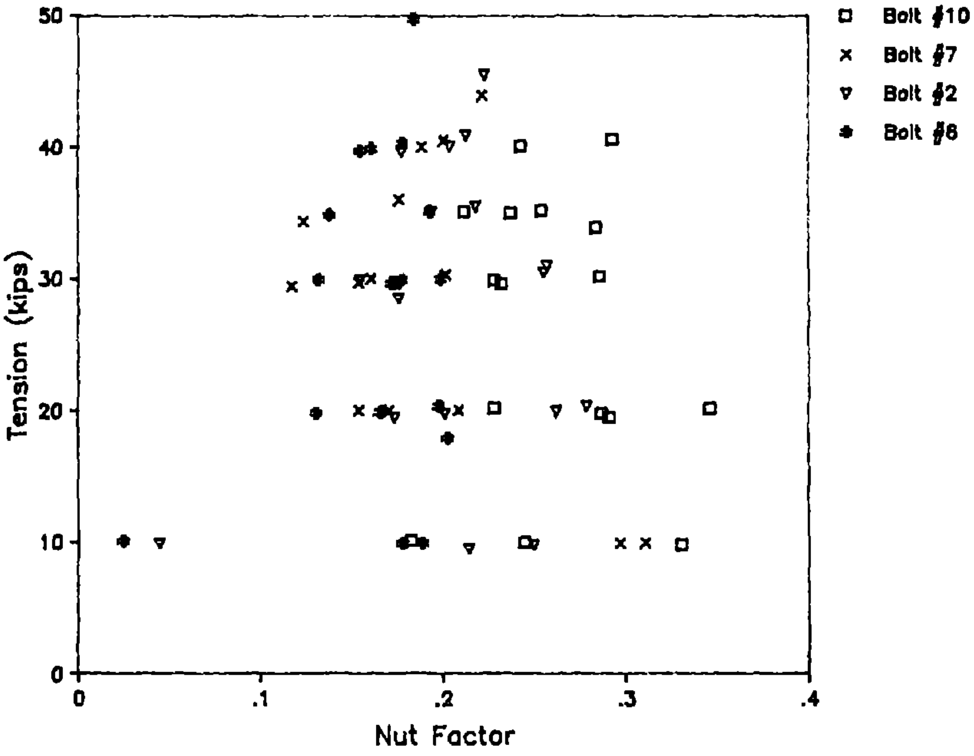


Figure 56. Nut factor of galvanized bolts removed from the bridge.

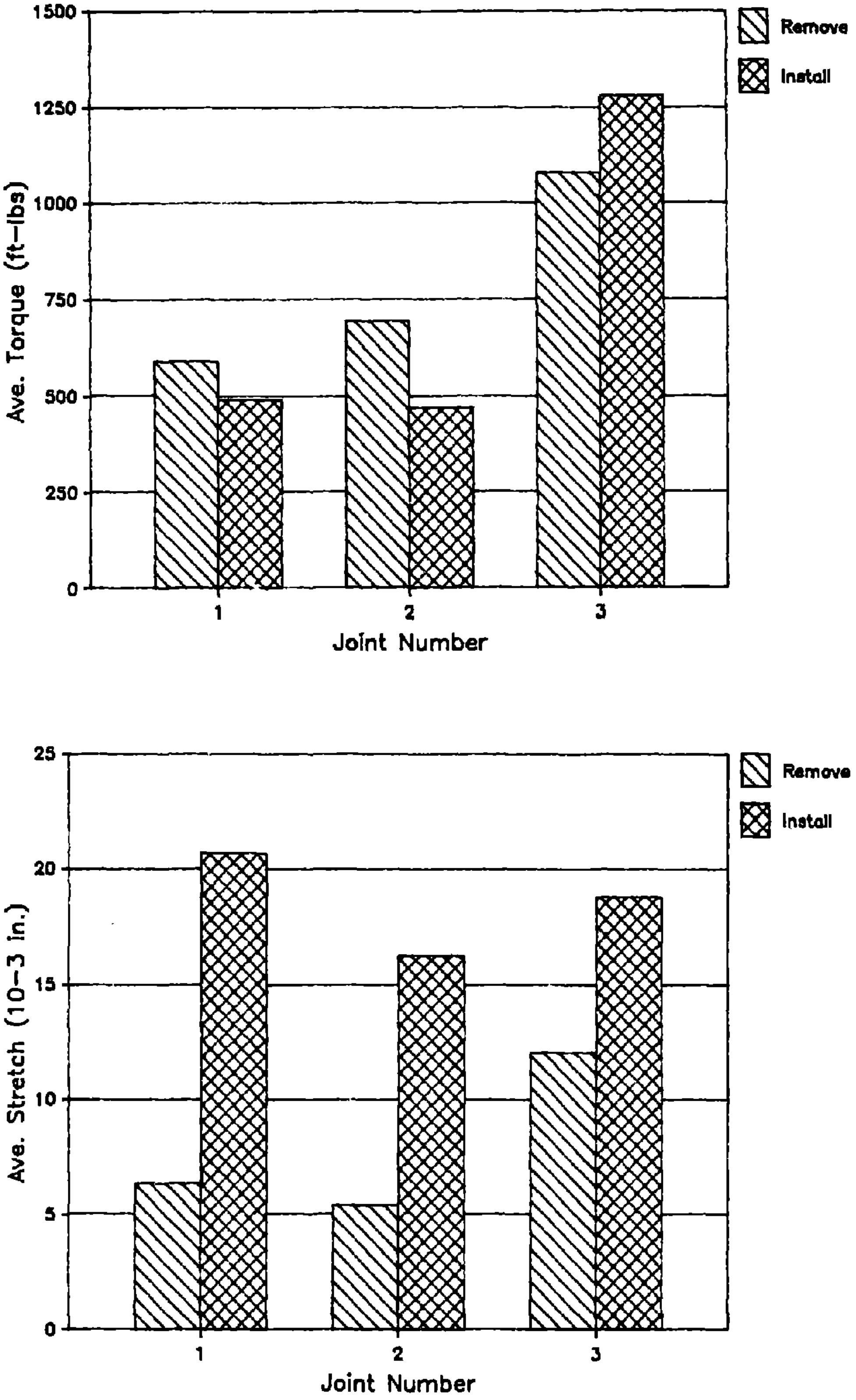


Figure 57. Average results of bridge bolts.

galvanized bolts are comparable to the black bolts tested in this research project. This indicates that galvanized bolts with proper thread fit and lubrication can be installed using equipment that is normally employed for good black bolts.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

Summary of Research and Observation

The tension-torque tests and solid-plate turn tests performed on the six lots of as-received hot dipped and mechanically galvanized bolts revealed that only one lot of bolts, the F lot, met the turn test requirement of the ASTM A325 specification. Lot F did not have the required minimum zinc thickness so none of the galvanized fasteners purchased on the open market satisfied the ASTM specification. All of the galvanized bolts with the exception of the hot dipped galvanized E bolts met the requirements after suitable nuts lubricated with commercial water soluble wax lubricants were used with the bolts. These results indicate that the required turn test is not being performed by the bolt supplier. The results also indicate that with standard commercial lubricants the desired performance can be easily attained.

Our visit to a major bolt and nut manufacturer revealed that the manufacturer did not understand the turn test. The manufacturer was performing the turn test in a Skidmore rather than in the solid plate required in ASTM. Due to the difference in stiffness, the test was invalid. A torque value which came from a table copied from another manufacturer's literature was used to see if the bolt reached the required tension. This is not part of the required test although it appeared that the quality control personnel doing the test believed otherwise. The manufacturer indicated that all galvanized bolts were tested in this manner on a shipping lot basis. ASTM A325 requires the test of two assemblies per shipping lot. The equipment used did not show the wear which would be indicative of that amount of testing nor did the personnel performing the tests appear to be familiar with the equipment or the incorrect procedures that were used. It should be noted that bolts supplied by the same manufacturer for the research project did not meet the ASTM turn test requirements; the bolts had severe stripping problems.

The basic problem with the turn test requirements is that no documentation of the tests is normally included in the standard bolt certifications. The purchaser has no documentation that the test has been performed. A second shortcoming of the ASTM requirements is that it is not clearly stated that the bolts should only be used with the nuts used in the turn test. Nuts from a different source, lubricated differently, with different hardness, or overtapped to a different size than the nuts used in the test may not perform satisfactorily. It is not clearly stated in the ASTM specifications that the nuts supplied with the bolts must match the nuts used in the turn test. It should also be made clear to the user of the bolts that the bolts are to be used only with the nuts supplied.

ASTM A325 refers to ASTM A563 in regard to the lubricant to be applied to galvanized nuts. There is no lubrication requirement for uncoated nuts. This is a dilemma since the commonly supplied 2H nut is not part of ASTM A563. ASTM A194 which contains the requirements for the 2H nut has no mention of galvanizing or lubrication of the nuts. The requirement for lubrication and the turn test of galvanized nuts are a supplementary requirement of A563. The nuts, bolts, and washer should be covered in one specification which clearly spells out all the requirements for testing and lubrication.

No where in the ASTM specifications is the efficiency of the lubricant specified. The only requirement is that the lubricant be clean and dry to the touch. The only way to specify the efficiency of a lubricant is to specify a nut factor that the lubricant should attain or a maximum torque for a specified load. It is very difficult using visual inspection to determine if a lubricant has been applied to a nut and whether the lubricant is proper. For example, a manufacturer could claim the nuts are lubricated if they are immersed in one of the commercial water soluble waxes used in this study diluted with 100 parts of water. This would not be a satisfactory lubricant; however, it would produce a clean and dry lubrication.

The wording of the ASTM specifications implies that lubrication is primarily used to prevent nut stripping. This is not true. Stripping is a strength problem. In fact, lubrication increases stripping problems. Lubrication is required on galvanized fasteners to reduce the thread galling so that the fastener assembly will have the same strength and rotation capacity as black bolts.

Bolt stripping is a thread strength problem. The empirical model developed by Alexander provides a reasonable indication of stripping behavior for black bolts but is slightly unconservative for overtapped nuts. This model as well as the test data developed in the present study show that the primary variables affecting stripping are the ratio of bolt to nut strength and the overlap of the threads or interface. High strength bolts with soft nuts will strip because the shear strength of the nut threads is not sufficient to develop the bolt's strength. Nuts which are overtapped can strip due to the loss of thread section. The requirement to use heat treated nuts with galvanized bolts is to ensure that the overtapped nut has sufficient strength on the reduced thread section to preclude stripping.

The ASTM A325 specification does not cover the amount of overtapping for a galvanized nut. The overtapping of the nuts is covered in A563, which has a poorly worded provision for overtapping requiring a minimum overtapping instead of clearly stating a maximum. The metric A325M specification clearly states a maximum but the allowable overtapping is too high. Bolts in this project as well as previous studies with nuts overtapped to the values specified in A563 failed predominately by stripping. The amount of overtapping required for thread clearance may be different for mechanically and hot dipped galvanized fasteners depending on the finish and thickness of the coating. The increase in the thread dimensions due to the zinc does not increase the thread strength. The stripping strength of the assembly is a function of the interface dimension of the steel part of the threads. Consequently, the maximum overtapping of a nut should be only that required to produce a good fit of the threads.

The A325 specification does not allow the mixing of mechanically and hot dipped galvanized nuts and bolts. Hot dipped bolts with mechanically galvanized nuts were used in some of the tests performed and were supplied as replacements to the assemblies removed from the field test bridge. These mixed assemblies worked very well, better than when the hot dipped nuts supplied with the bolts were used in the tests. The reason for the improved behavior was the smaller overtapping used in the mechanically galvanized nuts. If the assemblies are tested in the turn test and pass the test, there is no reason to require that the components have the same type of galvanizing.

It was obvious from the test results that most of the galvanized nuts purchased for use in the research project were not lubricated. This problem was discussed with a mechanical galvanizer. He pointed out that he often receives nuts for galvanizing which are then shipped directly to a warehouse or to a jobsite. The specification for galvanizing, ASTM B695, does not require that the nuts be lubricated after galvanizing. Consequently, the galvanized nuts are not lubricated when they are shipped directly to a suppliers warehouse or to a jobsite. Also the turn test could not be performed by the bolt supplier since the coated nuts were never in the bolt supplier's possession for testing. This situation occurs more frequently now because there are no domestic manufacturers that produce both nuts and bolts, and also do both types of galvanizing. Foreign bolts and nuts are often imported uncoated. A supplier may have the black imported bolts and nuts galvanized by another party. However these suppliers are typically unaware of the turn test, the lubrication requirements, and, in general, most test requirements in A325. Consequently, bolts and nuts are furnished without the turn test being performed and with unlubricated nuts.

The thickness of zinc on all the mechanically galvanized bolts failed to meet the the requirements of class 50 of ASTM B695. This is the required coating thickness in ASTM A325. None of the certification papers received with the galvanized bolts contained any zinc thickness measurements. Again, there is no way for a purchaser to determine if the bolts have been tested to determine if they meet the coating requirements based on the certification papers supplied with the bolts. The supplier should be required to provide the results of the coating thickness measurements on the certification documentation.

The A490 bolts tested in this project as well as in previous research showed very little ductility. The peak of the tension versus turn curve occurs at approximately the number of turns required in the turn of the nut installation procedure. This means that if the bolts were subjected to a slight amount of overturning they may be starting to fail. The result would be a reduced bolt tension or complete bolt failure. The torques required for the installation of these bolts are very large. The study by Notch indicates that these bolts are often not tightened correctly due to the large torques required for installation.[25, 26] In addition, the low ductility of these bolts may cause a brittle failure when they are used in tension applications. It is our recommendation that the use of A490 bolts be discouraged. This is strongly recommended for bolts greater then 1 in (25 mm) in diameter. Large A490 bolts are almost impossible to install with normal bolt tightening equipment.

There is overlap of some ASTM provisions that cause unnecessary problems and these should be eliminated. Type 2 bolts are described as low carbon yet the ASTM chemistry requirements permit a carbon content up to 0.37 percent in a product analysis. The Type 1 medium carbon bolt has a minimum carbon of 0.27 percent. Since there are some special requirements for hot dipped galvanized Type 2 bolts, would a bolt with 0.30 percent carbon and 0.005 percent boron be a Type 1 or a Type 2 bolt? Another area of overlap relates to galvanizing. ASTM permits the galvanizing of A325 bolts but not A490. A325 bolts 1 in (25 mm) or less in diameter are permitted to have a hardness of 35 on the Rockwell C scale. The minimum hardness in the A490 specification is 33. It makes no sense to permit galvanizing on a high hardness A325 bolt and not on a lower hardness A490 bolt.

The certification currently provided by vendors that their products meet specifications have little credibility. The problems uncovered on some fastener certifications are as follows:

- Only contain the results of some of the tests required by ASTM.
- Reports falsified.
- Certifications do not correspond to the bolts provided.
- Tests not conducted.

For example, the following statement appeared on one of the bolt certifications for the project:

> "The results of mechanical tests shown are of the last completed set of tests for the stock size in this shipment. The heat number and heat analysis shown are representative of heats used for our stock, but are not necessarily included in this shipment."

Such a certification is not a certification at all.

As far as tightening procedures are concerned, the major problems appear to be a lack of familiarity with proper bolting procedures and inspection. Notch has documented some of these problems, especially for large bolts.[25,26] Many inspectors use their past experience, often misguided, instead of the documented procedures in the Bolt Specification. Current provisions that permit no washers if turn-of-the-nut method is used also means the bolts cannot be inspected with a torque wrench. The following statements taken from Notch deserve special attention.[26]

> " Visits to several structural steel projects currently under construction with different steel erection crews revealed that, in most cases, the bolting crew was not following recommendations regarding the turn-of-the-nut method. Most bolting crews started their bolt-up at an arbitrary point within the connection's bolt pattern. Bolts were fully torqued one at a time without having first brought all the plies at the joint into contact with each other. A bolted structural connection, not unlike the wheel lugs of an automobile, requires snugging prior to final bolt torquing. The crews observed did not match mark bolts or even keep the part not turned by the wrench from rotating. Bolt impacting ceased when the bolt sounded tight. Bolt tightness was ascertained by the wrench operator's individual judgment; no consistent rules or guidelines of bolt tightness were used.

"Even when procedures are carefully followed, the elusive definition of 'snug tight' is a very real problem. As shown in Table 3, bolt tension at snug tight varies from 0 % to 43 % of the required maximum bolt preload. If the starting point of rotation cannot be well defined, the incremental rotation will not have meaning. Further compounding the problem of snug tight are bolts at large connections, whereby significant effort is required to pull the faying surface at the connection into contact.

"Although the calibrated torque wrench method of tightening was at one time disapproved by the specification, one wonders whether an improved version of the calibrated wrench, with more stringent calibration requirements as are now specified, would not give better results than the manner with which the turn-of-the-nut method is now being implemented on several of the major projects observed. Field test results on bolts for the specific project which had been ostensibly properly tightened via the turn-of-the-nut method and warranted as such by the independent testing laboratory have been found very erratic and not in compliance with the Code.

"Large diameter bolt usage
On the basis of discussions with many erectors, as well as personal observations, it would be recommended that engineers/fabricators/erectors shy away from the larger diameter high strength bolts, in particular, those of grade A490. Large diameter bolts stretch the limits of readily available impact wrench (slugging type) equipment. If the equipment is not relatively new and well maintained, or if air pressure is not carefully monitored, successful bolt tightening of these particular bolts is very hard to achieve. The odds of achieving a tight bolt are much improved with the smaller diameter bolts. Also, there are inherent benefits of designing with a large quantity of small diameter bolts in lieu of relying on the strength of a few large diameter bolts. If bolt failures do occur, or if minimum preloads are not achieved, the detrimental impact on the joint is much reduced with smaller diameter bolts. The engineering community should be apprised of the problems associated with large diameter bolts, so that potential problems can be avoided. In the future, if hydraulic-type wrenches could be designed that the steel erection community could accept and economically use, perhaps large diameter high strength bolting could be performed with confidence. This confidence does not exist with the impact-type equipment now being used on large diameter bolts."

Recommendations

Confidence in bolted construction needs to be reestablished. This can be accomplished through the cooperation of the Research Council on Structural

Connection, American Institute of Steel Construction, Fastener Institute, AASHTO, and ASTM Committee F-16 to develop a workable and enforceable set of specification and educational programs. Each one of these organizations is working separately within a narrow scope on self-defined aspects of bolted construction, but judging by the number of fastener assemblies that failed to perform properly in this program, the current system needs revision.

The objective is simple as illustrated in figure 58: to ensure that fastener assemblies consisting of a bolt, nut and washer like Lots L, F and H are delivered to the job site and assembly Lots G and E never arrive. To constitute good performance, high strength fasteners, black and galvanized subjected to a torqued-tension test should:'

- Go through 1-1/4 turns in a Skidmore (1 turn in solid plate) without failure, including stripping.
- Give a load at 1-1/4 turns not less than 90 percent of the maximum recorded tension.
- Require a recorded tension within the 1-1/4 turns of at least 80 percent of the minimum required tensile strength of the bolt.
- Permit a torque, at a load 5 percent greater than the minimum specified preload not greater than that given by equation 2, with the nut factor taken as 0.25.

The first item is necessary to define a minimum ductility for bolts in tension, to provide a factor of safety for the turn-of-nut installation method and to permit, even some inadvertent, reuse. Item 2 prevents rapid unloading so overtorquing and inspection torques will not significantly reduce clamping force. Item 3 transfers a RCSC Bolt Spec requirement into an ASTM and AASHTO Specification. It ensures that the required preload in the RCSC specification can be developed by the bolt-nut assembly. Item 4 is a check on the lubricant's efficiency so that common impact wrenches can be used to install the bolts and to fully utilize the bolt strength by minimizing torsional stresses. The test should be conducted by the supplier and the results given in the certification.

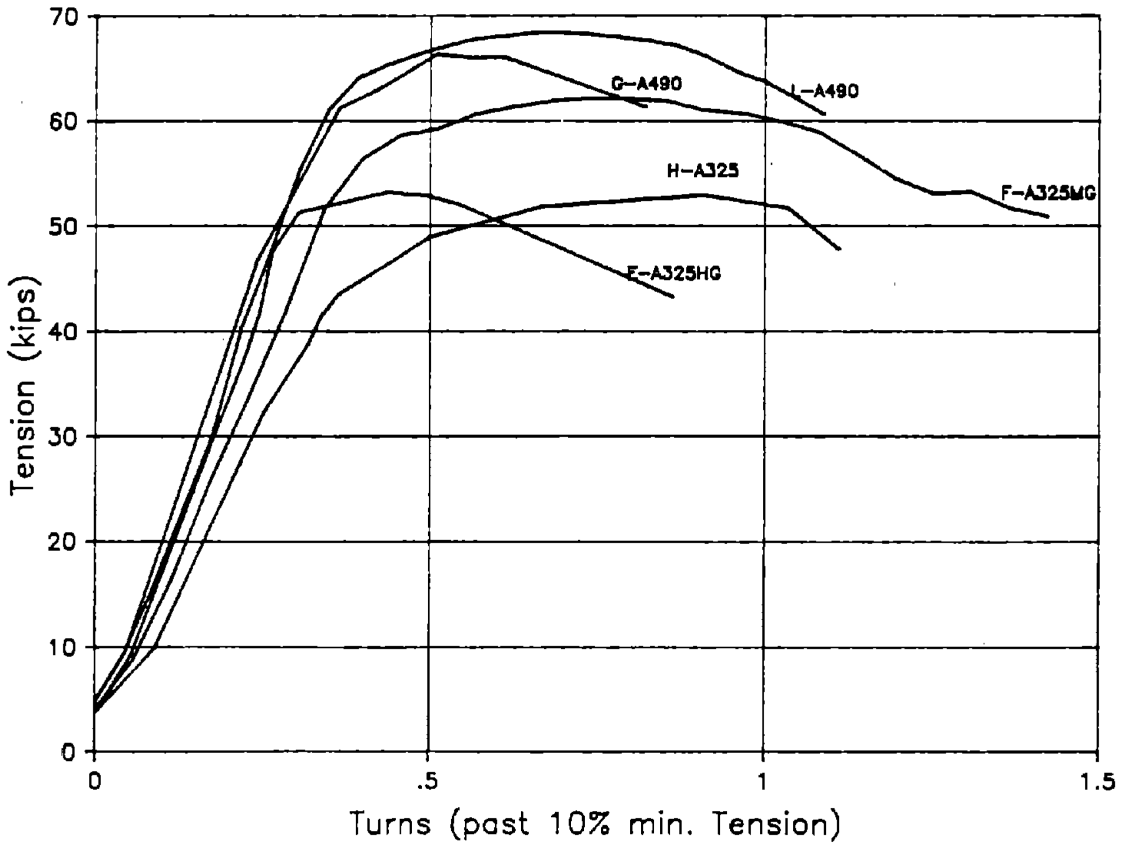


Figure 58. Fastener assembly behavior in solid plate.

It does not appear practical to expect that a nut and bolt manufactured under different ASTM Specifications and tested separately will ever provide assurance that the two elements can produce a good assembly. Since bolts are always used with nuts, it is recommended that all high strength bolts, nuts and hardened washers be covered under one ASTM designation, just like the Japanese Industrial Standard (JIS) for "Sets of High Strength Hexagon Bolt, Hexagon Nut and Plain Washers for Friction Grip Joints."[40] A copy of this standard cannot be produced herein because of copyright. Prior to 1978, A325 nuts and bolts were covered under one specification so the concept is not new. Most bolts and nuts are now purchased from vendors, not manufacturers. These vendors can continue to obtain products from a variety of sources but it should be their responsibility to combine the nuts and bolts into a system that works before delivery to the job site. Engineers currently assume that the ASTM specification requires the bolts to reach a minimum specified preload. The RCSC Specification requires this preload but not ASTM. In ASTM A325 only the turn test required for galvanized fasteners specifies that the nut and bolt be tested together.

The following specific suggestions are made:

- Require a lubricant on all nuts and use a dye in it so a check for the lubricant can be visual at the time of field installation.
- Increase the thread length of the bolt to the common $2D_s$ + 1/4-in to improve the bolt ductility, especially for A490.
- Revise the bolt certification so that zinc thickness and the result of the turn test and the torque test are given.
- Eliminate specific nut overtapping limits and hardness limits if the turn test is adapted as described above. However, based on current conditions, Grade C and D nuts should not be permitted and the overtap allowance for galvanized nuts should be reduced to 0.015 in (0.38 mm).
- Require that certification is provided for the assembly that is shipped with a corresponding lot number appearing on the shipping package and the certification.
- Eliminate overlaps in the ASTM Specification. Reduce the maximum carbon for Type 2 bolts to 0.25 percent and reduce the maximum hardness for A325 bolts from $35R_c$ to $32R_c$.
- Discourage the use of A490 bolts.

Until some of these recommendations can be adopted it is recommended that only DH nuts be permitted, that the specification to the vendors require the results of the turn test, which is now required, be given in writing and that inspectors and bolting crews be given access to the latest RCSC Bolt Spec where detail installation and inspection requirements are presented.

APPENDIX A

ASTM AND ANSI SPECIFICATIONS RELATED TO BOLTS AND NUTS

F606	Standard Method for Conducting Tests to Determine the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, and Rivets
A370	Standard Methods and Definitions for Mechanical Testing of Steel Products
A194	Carbon and Alloy Steel Nuts for Bolts for High-Pressure and High-Temperature Service
A325[M]	High Strength Bolts for Structural Joints [M = Metric]
A490[M]	Heat-Treated Steel Structural Bolts, 150 ksi Tensile Strength [M = Metric]
A563[M]	Carbon and Alloy Steel Nuts [M = Metric]
A153	Zinc Coating [Hot-Dip] on Iron and Steel Hardware
F436	Hardened Steel Washers
F959	Compressible-Washer-Type Direct Tension Indicators for use with Structural Fasteners
ANSI B1.1	Unified Screw Threads
ANSI B1.13M	Metric Screw Threads
ANSI B18.2.1	Square and Hex Bolts and Screws
B18.2.3.7M	Metric Heavy Hex Structural Bolts
B18.2.4.6M	Metric Heavy Hex Nuts

APPENDIX B BOLT AND NUT STRIPPING STRENGTH

The following formulas were adapted from Ref. 2 for the 7/8 in. (22 mm) bolts used in this research. Refer to Fig C for the definition of geometric terms.

The <u>bolt stripping load</u>, $B_s = 0.6F_bA_{sb}C_1C_2$ (6)

where

F_b = tensile stress of the bolt based on A_a

A_{sb} = shear area of the bolt threads

C_1 = nut dilation factor

C_2 = bolt thread bending factor

The <u>nut stripping load</u>, $N_s = 0.6F_nA_{sn}C_1C_3$ (7)

where

F_n = tensile stress of nut material (based on hardness)

A_{sn} = shear area of the nut threads

C_3 = nut thread bending factor

For 7/8 bolts with 9 threads/in., the following formulas apply:

$$C_1 = [-(F/D_s)^2 + 3.8(F/D_s) - 2.61] \qquad (8)$$

where F = width across flats of nut and D_s = diameter of bolt shank

$$A_{sb} = 16.32d[(L_E-H_B)(D-d + 0.024) + (d_m/d)H_B(D-d_m + 0.024] \qquad (9)$$

where d = smaller of d_w or d_n; d_m = larger of d_w or d_n,

$L_E = H - 0.048d - 0.039$

$A_{sn} = 16.32\ L_ED\ (D-d + 0.0722)$

$C_2 = 5.594 - 13.682\ R_s + 14.107\ R_s^2 - 6.057\ R_s^3 + 0.9353\ R_s^4$ if $1.0 < R_s\ 2.2$

$= 0.897$ if $R_s \leq 1.0$

$C_3 = 0.728 + 1.769R_s - 2.896R_s^2 + 1.296R_s^3$ if $0.4 < R_s < 1.0$

$= 0.897$ if $R_s \geq 1.0$

$R_s = (F_nA_{sn})/(F_bA_{sb})$

A 325

5.1 Type 1 and 2 bolts shall conform to the requirements as to chemical composition prescribed in Table 1.

TABLE 1 Chemical Requirements for Types 1 and 2 Bolts

Element	Composition, %	
	Type 1 Bolts	Type 2 Bolts[A]
Carbon:		
Heat analysis	0.28–0.55 min	0.15–0.38 → 0.24
Product analysis	0.25–0.58 min → 0.27	0.13–0.41 → 0.25
Manganese, min:		
Heat analysis	0.60	0.70
Product analysis	0.57	0.67
Phosphorus, max:		
Heat analysis	0.040	0.040
Product analysis	0.048	0.048
Sulfur, max:		
Heat analysis	0.050	0.050
Product analysis	0.058	0.058
Boron, min:		
Heat analysis	...	0.0005
Product analysis	...	0.0005

[A] Type 2 bolts shall be fully killed, fine grain steel.

6.1 Bolts shall not exceed the maximum hardness specified in Table 3. Bolts less than three diameters in length shall have hardness values not less than the minimum nor more than the maximum in hardness limits required in Table 3, as hardness is the only requirement.

TABLE 3 Hardness Requirements for Bolts

Bolt Size, in.	Hardness Number			
	Brinell		Rockwell C	
	Min	Max	Min	Max
½ to 1, incl	248	331 → 302	24	35 → 32
1⅛ to 1½, incl	223	293	19	31

The maximum carbon of Type 2 bolts overlaps the minimum value of Type 1 bolts. This does not permit a chemical analysis to distinguish between the two types. Return the values to those in earlier editions of the ASTM A325 Specifications, as shown.

The hardness requirements for A490 bolts are 33 min to 38 max, Rockwell C. Thus the maximum hardness limit for small diameter A325 bolts of 35 R_C exceeds the minimum for A490. Reduce the maximum hardness for A325 bolts to eliminate this overlap.

1.7 Unless otherwise specified, all nuts used on these bolts shall conform to the requirements of Specification A 194 or A 563, shall be heavy hex, and shall be of the class and surface finish for each type of bolt as follows:

Bolt Type and Finish	Nut Class and Finish
1 and 2, plain (noncoated)	A 563 - ~~C, C3, D,~~ DH, DH3, plain ~~A 194 - 2, 2H, plain~~
1 and 2, galvanized	A 563 - DH, galvanized ~~A 194 - 2H, galvanized~~
3, plain	A 563 - ~~C3,~~ DH3, plain

Eliminate C, C3, D, 2 and 2H nuts. Permit only DH and DH3 nuts because of stripping problems.

1.5 Zinc-coated Type 2 bolts and studs shall be coated by the mechanical deposition process only.

~~6.6 When hot-dip zinc-coated Type 2 bolts are supplied, they shall be tension tested after galvanizing in accordance with 6.2 or 6.3 depending on the diameter. The number of tests from each lot shall be in accordance with 9.2.4 or 9.3.4.~~

Section 6.6 is not needed since only the mechanically deposited process is permitted with Type 2 bolts.

7.2 Threads shall be the Unified Coarse Thread Series as specified in ANSI/ASME B1.1, and shall have Class 2A tolerances. ~~When specified,~~ The 8-pitch thread series ~~may~~ shall be used on bolts over 1 in. in diameter.

Great difficulty is encountered in tightening large diameter bolts if very coarse threads are used. Turn-of-nut tightening method would be questionable if a pitch less than one-to-eight is used.

4.4 *Zinc Coatings, Hot-dip and Mechanically Deposited:*

~~4.4.1 When zinc-coated fasteners are required, the purchaser shall specify the zinc coating process, for example, hot dip, mechanically deposited, or no preference.~~

~~4.4.2 When hot-dip is specified, the fasteners shall be zinc-coated by the hot-dip process in accordance with the requirements of Class C of Specification A 153.~~

~~4.4.3 When mechanically deposited is specified the fasteners shall be zinc-coated by the mechanical deposition process in accordance with the requirements of Class 50 of Specification B 695.~~

~~4.4.4 When no preference is specified, the supplier may furnish either a hot-dip zinc coating in accordance with Specification A 153, Class C or a mechanically deposited zinc coating in accordance with Specification B 695, Class 50. All components of mating fasteners (for example, bolts, nuts, and washers) shall be coated by the same zinc-coating process and the suppliers option is limited to one process per item with no mixed processes in a lot.~~

Replace section 4.4 with the following:

When zinc coating is required by the purchase order, the supplier has the option of furnishing either hot-dip galvanizing (Class C of ASTM A153) or mechanically-dposited zinc (Class 50 of ASTM B695) products unless the specific process is called for on the purchase order. It is not necessary that the bolt, nut, and washer used in the fastener assembly be coated by the same zinc process, i.e. hot-dip or mechanically deposited, unless required in the purchase order.

13. Certification

~~13.1 *Bolts*—When specified on the order the manufacturer shall furnish the test reports described in 9.2.7 or 9.3.6, depending on whether the bolts are furnished by the production lot or shipping lot method.~~

Replace with the following:

Bolt suppliers shall provide the purchaser with the following information related to the specific bolt lots in the delivery

- The city and country where the bolts were manufactured.
- The tensile strength and the date tested except for bolts less than three diameter in length.
- The hardness value and the date tested.
- For zinc coated bolts and nuts, the result of the rotation capacity test described in Section 6.5, and the date tested.
- The measured thickness of the zinc coating for galvanized bolts, and the date tested.

The lot number of the delivered bolts must appear on the certification.

8.5 The zinc-coated bolt shall be placed in a steel joint and assembled with a zinc-coated washer and a zinc-coated nut with which the bolt is intended to be used. The nut shall have been provided with the lubricant described in 4.8 of Specification A 563. The joint shall be one or more flat structural steel plates with a total thickness, including the washer, such that 3 to 5 full threads of the bolt are located between the bearing surfaces of the bolt head and nut. The hole in the joint shall have the same nominal diameter as the hole in the washer. The initial tightening of the nut shall produce a load in the bolt not less than 10 % of the specified proof load.[12] After initial tightening, the nut position shall be marked relative to the bolt, and the rotation shown in Table 8 shall be applied. During rotation, the bolt head shall be restrained from turning.

Insert the following:

Alternatively, a Skidmore-Wilhelm hydraulic bolt calibrator may be used instead of solid plates.

TABLE 8 Test for Zinc-Coated Bolts

Bolt Length, in.	Nominal Nut Rotation, ~~deg (turn)~~
Up to and including 4	~~300 (5/6)~~
Over 4, but not exceeding 8	~~360 (1)~~
Over 8	~~420 (1 1/6)~~

Add a column of nut rotation for a hydraulic calibrator

Nominal Nut Rotation

Solid Plate deg (turn)	Skidmore-Wilhelm deg (turn)
300 (5/6)	390 (1-1/12)
360 (1)	450 (1-1/4)
420 (1-1/6)	510 (1-5/12)

---

[12] Use of the torque value obtained in a Skidmore-Wilhelm calibrator, or equivalent, may be used in meeting this requirement.

4.7 *Zinc Coatings, Hot-Dip and Mechanically Deposited:*

~~4.7.1 When zinc-coated fasteners are required, the purchaser shall specify the zinc coating process, for example, hot-dip, mechanically deposited, or no preference.~~

~~4.7.2 When hot-dip is specified, the fasteners shall be zinc-coated by the hot-dip process in accordance with the requirements of Class C, of Specification A 153.~~

~~4.7.3 When mechanically deposited is specified, the fasteners shall be zinc coated by the mechanical deposition process in accordance with the requirements of Class 50 of Specification B 695.~~

~~4.7.4 When no preference is specified, the supplier may furnish either a hot-dip zinc coating in accordance with Specification A 153, Class C, or a mechanically deposited zinc coating in accordance with Specification B 695, Class 50. All components of mating fasteners (bolts, nuts, and washers) shall be coated by the same zinc-coating process and the supplier's option is limited to one process per item with no mixed processes in a lot.~~

When zinc coating is required by the purchase order, the supplier has the option of furnishing either hot-dip galvanizing (Class C of ASTM A153) or mechanically-deposited zinc (Class 50 of ASTM B695) products unless the specific process is called for on the purchase order.

4.8 Hot-dip and mechanically deposited zinc-coated Grade DH nuts shall be provided with an additional lubricant which shall be clean and dry to the touch.

The lubricant shall have a color so that its presence is visually obvious at the job site.

7.4 ~~Nuts to be used on bolts threaded with Class 2 A threads before hot-dip zinc coating, and then hot-dip zinc-coated in accordance with Specification A 153, Class C, shall be tapped oversize at least by the following minimum diametral amounts:~~

Diameter, in.	in.[4]	
7/16 and smaller	0.016	
Over 7/16 to 1	~~0.021~~	0.015
Over 1	0.031	0.025

Replace with the following:

Galvanized nuts to be used with galvanized bolts, that are tapped oversize, shall have the maximum limit for pitch and minor diameters for Class 2A threads increased by the following diametral amounts:

---

[4] Applies to both pitch and minor diameters, minimum and maximum limits.

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