# Tightening of High Strength Metric Bolts

**by**

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Approved by
Supervising Committee:

Karl H. Frank

Joseph A. Yura

*To my family*

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The mandated use of metric dimensions and designs for new highway construction requires the use of metric dimension fasteners. Even though the ASTM Specifications A325M and A490M for metric high strength bolts have been available for almost 20 years, they have not been used in any U. S. construction and have only been manufactured in a test lot by one U. S. manufacturer.

This research examines the influence of bolt length, grip length, bolt strength, and thread lubrication on the relationship between nut rotation and bolt tension. Two different diameters of A325M metric bolts were tested: 24 mm bolts with lengths of 70, 100, and 120 mm, and 20 mm bolts with lengths of 50, 60, and 70 mm. The performance results for the two sizes of fastener are evaluated and compared with the present nut rotation requirements for inch fasteners. The results are used to set installation requirements for the turn-of-the-nut procedure and make all required changes to the rotational capacity test to accommodate metric fasteners.

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# CHAPTER 1

# INTRODUCTION

## 1.1 INTRODUCTION

The mandated use of metric dimensions and designs for new highway construction requires the use of metric dimension fasteners. The ASTM Specifications A325M and A490M for metric high strength bolts, which were first published in 1979, have never been utilized. The specifications were developed in response to early metrification programs. These specifications differ from the European and Japanese specifications for similar bolts. The thread form, nut height, and nut strength are different from foreign specifications. The ASTM specifications were developed to provide a fastener which would behave similar to the present inch series bolts. Even though these specifications have been available for almost 20 years, they have not been used in any U. S. construction and have only recently been manufactured in a test lot by one U. S. manufacturer.

The Texas Department of Transportation (TxDOT) requires the use of the turn-of-the-nut installation method, and requires the manufacturer and installer to perform a rotational capacity test of the fastener assembly. The turn-of-the-nut installation method presently used was developed for inch fasteners and has never been examined using fasteners manufactured to metric specifications. A limited number of tests have been reported by two bolt manufacturers comparing cap screw metric bolts with equivalent inch series bolts. The results indicate that the metric fasteners do not provide the same tension for a given rotation as the inch bolts. Research to determine the correct method of installing metric fasteners by the turn-of-the-nut method is needed. In addition, any modifications to the rotational capacity test to accommodate the different behavior of the metric fasteners must be determined prior to requiring this test.

## 1.2 PROJECT SCOPE

The research examines the influence of bolt length, grip length, bolt strength, and thread lubrication on the relationship between nut rotation and bolt tension. Two different diameters of A325M metric bolts were tested: 24 mm bolts with lengths of 70, 100, and 120 mm, and 20 mm bolts with lengths of 50, 60, and 70 mm. The performance results for the two sizes of fastener are evaluated and compared with the present nut rotation requirements for the inch fasteners. The results are used to set installation requirements for the turn-of-the-nut procedure and make any required change to the rotational capacity test to accommodate metric fasteners.

## 1.3 PROJECT OBJECTIVE

The overall goal of the A325M bolt research project is determine the correct method of installing and testing metric fasteners. The results and conclusions presented in this report are intended to increase the reliability of bolted connections and to provide necessary data relevant to the behavior of metric fasteners as the bridge industry makes the transition to the metric system.

# CHAPTER 2

# THEORETICAL BACKGROUND

## 2.1 INTRODUCTION

The turn-of-the-nut installation method specifies a nut rotation range to produce a bolt tension which exceeds the minimum required fastener tension for slip critical and direct tension connections. This procedure is based on thorough research on the performance characteristics of A325 and A490 inch bolts. To date, only one manufacturer has attempted to make a fastener to the ASTM A325M metric specifications. As a result, there has been minimal research on the behavior of metric structural steel fasteners. The differences between the A325M and A325 bolts, however, are enough to warrant research to determine the applicability of the turn-of-the-nut method and the rotational capacity test to metric bolts.

## 2.2 TURN-OF-THE-NUT TIGHTENING

The tightening behavior of a bolt-nut-washer assembly can be characterized by plotting the tension induced by the tightening process against the number of turns of the nut. Nut turns are measured from a snug tight condition, defined by the AASHTO Specification [13] as “the tightness that exists when the plies of the joint are firm in contact. This may be attained by a few impacts of an impact wrench or the full effort of a man using an ordinary spud wrench".

Figure 2.1 shows the idealized behavior of a fastener installed using the turn-of-the-nut procedure. The fastener has a long inelastic plateau in which the installed fastener tension is not appreciably affected by the nut rotation. Failure occurs by either bolt fracture or stripping of the bolt or nut. The nut rotations within the tolerances specified in the ASTM Specification are designed to produce an installation tension that exceeds the required minimum.

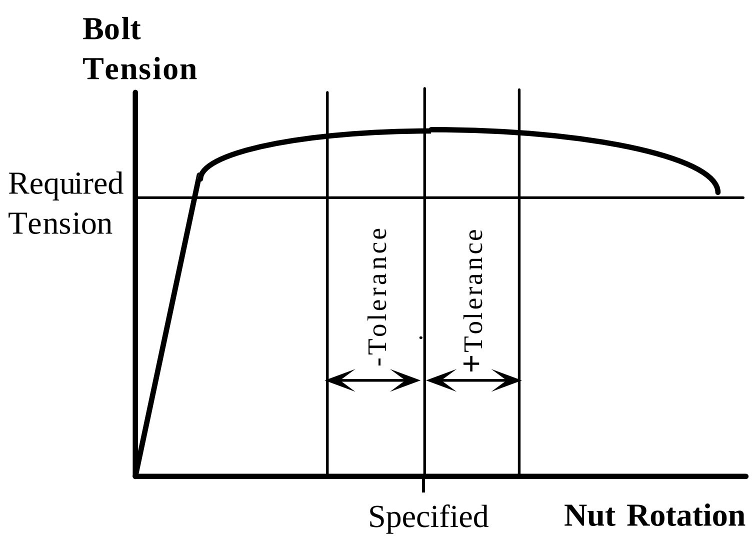


***Figure 2.1 Sample Tension-Turn Relationship for A325 Bolt***

For slip-critical connections and connections subjected to direct tension, the minimum required fastener tension is equal to 70 percent of the specified minimum tensile strength of the bolt. The specified nut rotation values to reach the required fastener tension were determined in previous research on A325 and A490 inch bolts. These nut rotation requirements are presented in Table 2.1.

***Table 2.1 AASHTO Required Nut Rotation From Snug Condition to Reach 70 Percent of Minimum Tensile Strength of Bolts [a,b]***

| **Bolt Length** | **Disposition of Outer Face of Bolted Parts** | | |
|---|---|---|---|
| (underside of head to end of bolt) | Both Faces normal to bolt axis. | One face normal to bolt axis and other sloped not more than 1:20 (beveled washer not used) | Both faces sloped not more than 1:20 from normal to the bolt axis (beveled washer not used) |
| Up to and including 4 diameters | 1/3 turn | 1/2 turn | 2/3 turn |
| Over 4 diameters but not exceeding 8 diameters | 1/2 turn | 2/3 turn | 5/6 turn |
| Over 8 diameters but not exceeding 12 diameters [c] | 2/3 turn | 5/6 turn | 1 turn |

a. Nut rotation is relative to bolt regardless of the element (nut or bolt) being turned. For bolts installed by 1/2 turn and less, the tolerance should be plus or minus 30 degrees; for bolts installed by 2/3 turn and more, the tolerance should be plus or minus 45 degrees.
b. Applicable only to connections in which all material within the grip of the bolt is steel.
c. For bolt lengths exceeding 12 diameters, the required rotation must be determined by actual tests in a suitable tension measuring device which simulates the actual conditions.

## 2.3 FACTORS AFFECTING BOLT PERFORMANCE

The shape of the tension-turn curve depends on a variety of factors such as the bolt strength, grip length, lubrication, and stiffness of bolted material or test setup. Each of these variables can significantly alter the relative performance of the fastener.

### 2.3.1 Grip Length

The grip length is the total thickness of material between the head of the bolt and the washer face of the nut, exclusive of washers. Figure 2.2 shows the relative behavior of bolts with the same mechanical properties and lubrication but with larger and smaller grip lengths. These tension-turn curves are graphed along with the ideal behavior for the turn-of-the-nut procedure. The initial slope, R, of the curves is essentially linear elastic. In the elastic range, the relationship between the nut rotation, N, and the tension induced in the bolt, T, is defined by the relationship,

$$N = (T \times L)/(A_e \times E \times P) \qquad (2.1)$$

where L is the grip length, $A_e$ is the effective bolt area, E is Young's Modulus, and P is the thread pitch. Therefore, the number of turns required to reach a specific fastener tension is directly proportional to the grip length. A bolt with a long grip length requires more turns to reach the required tension than a shorter bolt with the same diameter.

The grip length is made up of the shank length and the threads in the grip. Because the shank is inherently stiffer than the threaded portion of the grip, the thread length within the grip affects the bolt behavior. As the thread length within the grip decreases, the maximum strength increases but the ductility decreases [5].

The turn-of-the-nut installation requirements based upon bolt length are designed to ensure that the bolt with the longer grip length will not have a tension less than the required at the lower bound value for required turns, and that the bolt with the shorter grip length does not fracture or have a tension less than required at the upper bound value for required turns as shown in Figure 2.2.

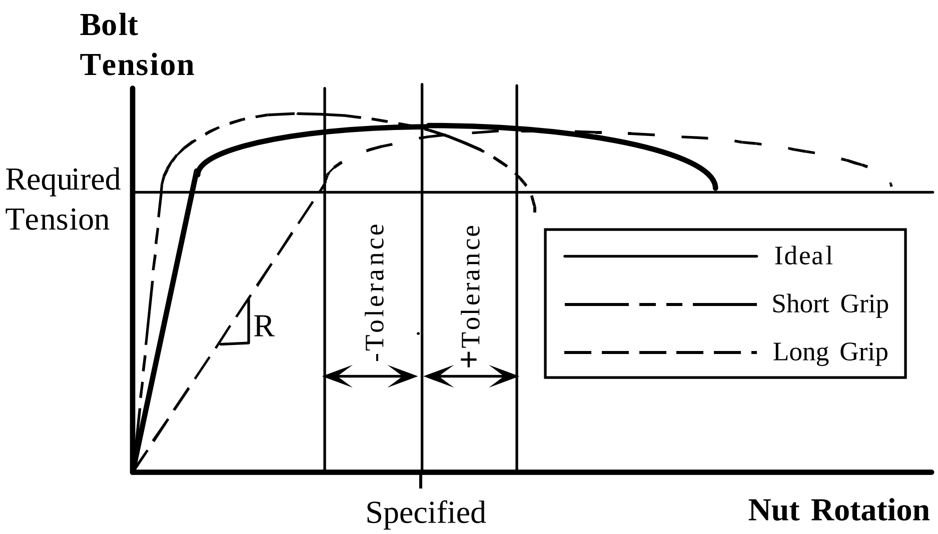


***Figure 2.2  Effect of Grip Length on Bolt Behavior***

### 2.3.2  Lubrication and Installation Torque

Tightening a bolted connection by turning the nut introduces torsion as well as tension into the bolt.  The presence of torsional stress has a very significant effect on the tension-turn response of a fastener assembly.  Research indicates that the torqued tension is typically 10 to 20% lower than the direct tension results [8 and 10].  The actual reduction in maximum tension is very sensitive to lubrication and thread conditions.

Three factors contribute to the resistance encountered in turning a nut. Energy or torque is required to force the nut up the inclined planes of the thread, to overcome the friction on the threads at the bolt nut interface, and to overcome the friction between the nut, washer, and the gripped material. Studies have shown that 90 percent of the energy will go into overcoming the friction. Therefore, lubrication on the nut face and threads is required to reduce the torque input. In one study with a lubricant called "No-Oxide" on the nut threads and surface of A325 bolts, the torque was only 67% of that measured in the unlubricated state [7]. By lowering the torque, lubrication reduces the overall power requirements for installing high strength bolts and speeds up the tightening process.

Lubrication also has a significant effect on the tension-turn curve. Lack of lubrication significantly reduces the strength and ductility of bolts, as shown in Figure 2.3. In a study performed by Eaves at The University of Texas at Austin, A325 and A490 fasteners cleaned of lubricant (weathered) were found to fail before the minimum specified bolt tension was reached. Installation torques were 60 percent higher for the clean threads in this case [8]. Torsion in a bolt increases as the bolt-nut thread friction increases. The combined state of stress reduces maximum tension and ductility.

The decrease in ductility should be taken into account when determining the effectiveness of the current nut rotation requirements. A short bolt at the maximum specification strength level with lesser lubrication, that is still acceptable based on the nut factor requirement in the rotational capacity test, should be used to determine the upper bound value of required nut rotation. Similarly, a lower strength long bolt with lesser lubrication should be used to determine the minimum required installation turns.

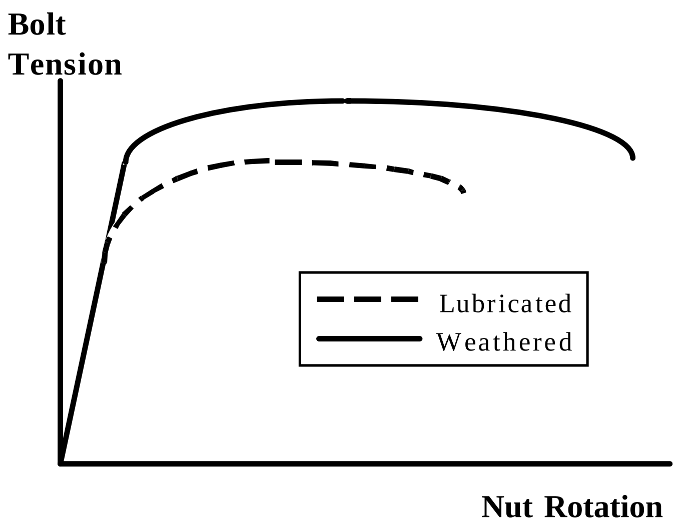


***Figure 2.3 Effect of Poor Lubrication / High Installation Torque on Bolt Behavior***

The measured relationship between torque and tension in an A325 bolt-nut-washer assembly is reasonably linear up to near maximum load. The commonly used relationship,

$$\text{Torque} = K \times P \times D \qquad (2.2)$$

relates the torque to the desired bolt tension, P, and the nominal diameter of the bolt, D. K is a dimensionless nut factor which depends on the material and the surface conditions of the threads, nut and washer. K was found to be between 0.18 and 0.29 for a wide variety of conditions in the field [6]. The Japan Industrial Standard [12] uses the same relationship between torque and tension, with the K factor ranging between 0.11 and 0.19 [9]. As a result of the wide variation in K values, the current RCSC specification requires that the actual torque-tension relationship (nut factor) must now be determined by an on-site calibration. In the rotational capacity test, the maximum allowable nut factor is 0.25.

### 2.3.4 Stiffness of Test Setup

Hydraulic bolt calibrators are typically used to conduct tension-turn calibration tests. These bolt calibrators have a lower stiffness than the solid plate connection configurations encountered in practice. During a test, the hydraulic bolt calibrators exhibit larger deformations than solid plate and solid plate load cell setups at the same tensile load.

In the turn-of-the-nut procedure, nut rotation is used to control strain and induce tension in the fastener. Nut rotation is used to calibrate bolt performance rather than bolt elongation. As a result, the nut rotation corresponding to a tension value in a hydraulic calibrator may be larger than the nut rotation to reach the same tension value in a solid plate setup. Various comparisons of Skidmore-Wilhelm bolt calibrator tension-turn curves to solid plate tension-turn curves for inch bolts are published. In the elastic range, the Skidmore may indicate 25 to 75 percent more turns to reach the minimum specified tension than are required in a solid steel assembly [7]. Real connections typically have multiple ply "out of flat" plates. The total stiffness of these connections falls in between the stiffness of a hydraulic bolt calibrator and a solid plate. Therefore, a tension-turn test in a hydraulic bolt calibrator overestimates the required turns to the minimum specified tension value for a stiffer connection configuration. However, the results of solid plate tension-turn tests provide an upper bound stiffness for an actual multiple ply connection, and are necessary to ensure that the larger number of turns does not lead to bolt failure or a decrease in fastener tension below the required minimum.

## 2.4 ROTATIONAL CAPACITY TEST

The rotational capacity test is performed to check the performance of the bolt-nut-washer assemblies from each lot intended for installation.

### 2.4.1 Hydraulic Bolt Tension Calibrator

A standard torque wrench is used to tighten the bolt assembly in a Skidmore-Wilhelm bolt tension calibrator or equivalent tension measuring device. The bolt is tightened to a snug tension equal to 10 percent of the specified minimum required installation tension. The nut is turned until the fastener tension exceeds the minimum required installation tension. At this point, an additional reading of tension and torque is recorded. The recorded torque value must not violate the following equation,

$$\text{Torque} < 0.25 \times P \times D \qquad (2.3)$$

where P is the fastener tension and D is the nominal bolt diameter.

The nut is then turned to a rotation equal to 2 times the minimum required nut rotation. The minimum tension induced in the bolt at this rotation must be equal to or greater than 1.15 times the minimum required installation tension.

After the nut has been turned to the required rotation, the bolt assembly must show no signs of failure. Failure is defined as inability to achieve the required rotation, inability to remove the nut following the test, shear failure of the threads, or torsional failure of the bolt.

### 2.4.2 Steel Joint

Bolts with lengths too short to be tested in the hydraulic bolt calibrator are tested in a steel joint. The test is essentially the same as with the bolt tension calibrator, except that the minimum turn test tension cannot be measured and does not apply. However, the torque at any point in the test cannot violate the previous limiting equation (2.3) with an assumed tension taken as 1.15 times the minimum required tension.

## 2.5 Differences Between A325M and A325 Bolts

### 2.5.1 Thread Pitch

The thread pitch for a metric bolt is less than for a comparable inch fastener. The thread pitches for the inch and metric bolts are shown in Figure 2.4. With lower thread pitches, the elongation induced by a turn of the nut will be less for the metric bolts. As a result, the nut rotation requirements to reach the minimum specified fastener tension in an inch bolt may not be valid for metric bolts.

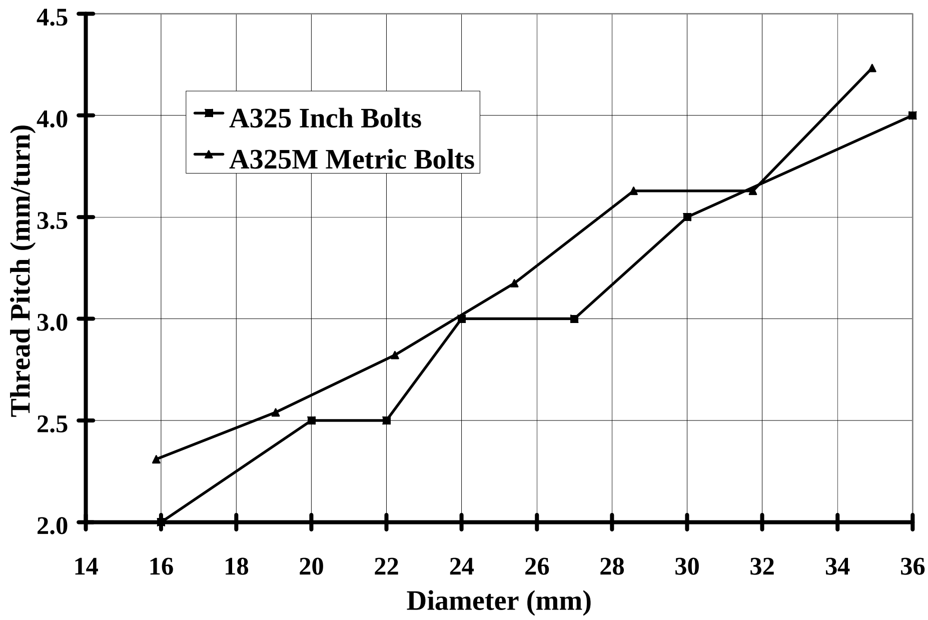


*Figure 2.4  Comparison of Thread Pitches for A325 and A325M Bolts*

### 2.5.2 Reduction in Required Strength for Larger Bolts

The A325M Specification does not reduce the required strength for large diameter bolts. The present inch specification reduces the tensile strength requirements on bolts larger than 25.4 mm. These differences may influence the tightening behavior of the fasteners. The smaller pitch of the metric fastener will reduce the deformation and consequently the tension introduced in the bolt when the turn-of-the-nut method of installation is used. The higher strength requirements of the larger A325M bolts may reduce their ductility. The lower ductility may require a reduction in the overtightening tolerance of the fastener and influence its acceptance criteria in the rotational capacity test.

### 2.5.3 Hole Size

The standard inch hole is 1.6 mm larger than the fastener. The standard metric hole is 2 mm larger than the bolt for bolts up to and including 24 mm bolts and 3 mm for larger bolts. This larger hole size increases the stress on the connected plates under the nut and bolt head. As a result, the deformation of the plates under these elements will be larger than in the inch bolts. The increased deformation of the plates will reduce the deformation introduced into the fastener for a given nut rotation. This phenomena is recognized in the present inch bolt installation specification by the requirements for the use of washers when A490 bolts are used with A36 material and the washer requirements for oversize holes.

# CHAPTER 3

# TEST PROGRAM

## 3.1 INTRODUCTION

Two general types of tests were conducted: one to measure the material characteristics of the bolts and nuts, and a second to study the performance of the bolt-nut-washer assembly. Chemistry composition, hardness, and direct tension tests were conducted on the bolts and nuts. Two different types of tests were performed on the bolt-nut-washer assembly: torque-tension-turn tests in setups of varying stiffness and tension-turn tests in solid plates. The method of testing and a description of these test setups is presented in this chapter. The results of the material tests are shown and compared with the applicable specifications. The results of the torque-tension-turn and tension-turn tests are presented in Chapter 4.

## 3.2 FASTENER PROPERTIES

Two different diameters of A325M bolts were examined in this project: 24 mm and 20 mm. The 24 mm bolts had lengths of 70 mm, 100 mm, and 120 mm. The 20 mm bolts had lengths of 50 mm, 60 mm, and 70 mm. Chemistry composition, hardness, and direct tension tests were performed on the bolts and nuts to verify the mill test results.

### 3.2.1 Dimensions

The bolt and nut dimensions shown in Tables 3.1 and 3.2 are averages of three samples of each specimen type. The relevant ANSI dimension tolerances for each bolt and nut are presented in Tables 3.3 and 3.4 [1 and 2]. The measured dimensions all fall within the specified tolerances, with the exception of the major diameter of the threaded portion of each bolt. The major diameter exceeds the maximum ANSI tolerances.

### 3.2.2 Chemistry Composition

Weight percent chemical analysis tests of the bolt and nut specimens were performed by both the mill and an independent testing laboratory. The results of these tests are presented in Tables 3.5, 3.6, and 3.7. The silicon content of the specimens was not determined by the independent testing laboratory. The ASTM Chemical Requirements [3 and 4] for the bolts and nuts tested in this analysis are shown in Table 3.8. The weight percent heat analysis results indicate that the fasteners and nuts meet the require specifications for composition. The chemical weight percentages are within the ASTM required ranges for all the specimens.

*Table 3.5 Chemistry Composition of 24 mm Bolts*

| Chemistry Composition | Mill Test | Lab Test | | |
|---|---|---|---|---|
| **Wt % Heat Analysis** | **Heat** | **70 mm** | **100 mm** | **120 mm** |
| **C** | 0.38 | 0.384 | 0.395 | 0.383 |
| **Mn** | 1.06 | 1.096 | 1.099 | 1.100 |
| **P** | 0.008 | 0.011 | 0.010 | 0.012 |
| **S** | 0.016 | 0.010 | 0.010 | 0.010 |
| **Si** | 0.21 | - | - | - |
| **B** | N. R. | 0.0012 | 0.0012 | 0.0014 |

*Table 3.6 Chemistry Composition of 20 mm Bolts*

| Chemistry Composition | Mill Test | Lab Test | | |
|---|---|---|---|---|
| **Wt % Heat Analysis** | **Heat** | **50 mm** | **60 mm** | **70 mm** |
| **C** | 0.36 | 0.38 | 0.38 | 0.38 |
| **Mn** | 1.09 | 1.14 | 1.14 | 1.16 |
| **P** | 0.007 | 0.010 | 0.009 | 0.009 |
| **S** | 0.023 | 0.024 | 0.023 | 0.023 |
| **Si** | 0.23 | - | - | - |
| **B** | N. R. | 0.0004 | 0.0003 | 0.0003 |

***Table 3.7 Chemistry Composition of 6H GR10S Nuts***

| Chemistry Composition | Mill Test | | Lab Test |
|---|---|---|---|
| **Wt % Heat Analysis** | **M24-3.0** | **M20-2.5** | **M20-2.5** |
| **C** | 0.43 | 0.44 | 0.45 |
| **Mn** | 0.67 | 0.66 | 0.69 |
| **P** | 0.009 | 0.007 | 0.008 |
| **S** | 0.022 | 0.016 | 0.022 |
| **Si** | 0.24 | 0.20 | - |

***Table 3.8 ASTM Chemical Requirements for Bolts and Nuts***

| Chemistry Composition | A325M Type 1 Bolt | A563M Nut |
|---|---|---|
| **Wt % Heat Analysis** | **Alloy Steel** | **10S Property Class** |
| **C** | 0.30 - 0.52 | 0.55 max. |
| **Mn** | 0.60 min. | 0.30 min. |
| **P** | 0.035 max. | 0.04 max. |
| **S** | 0.040 max. | 0.05 max. |
| **Si** | 0.15 - 0.35 | - |
| **B** | - | - |

### 3.2.3 Hardness Tests

The bolt hardness was measured at 1/8 diameter intervals on two perpendicular axes through the shank of the bolt. The hardness readings on the nuts were taken on one of the flat sides that was machined down a few thousandths of an inch, following ASTM F606 recommendations. Rockwell hardness values and measurement locations for each bolt diameter are presented in Figure 3.1. The tests show that the hardness is higher on the outer portion of the bolt, but these results are not abnormal. This hardness pattern indicates that the bolts were properly heat treated.

The average 1/4 diameter hardness values for each bolt and nut are given in Table 3.9, along with the average mill test results. The lab bolt hardness data represents the average of the readings taken at 1/4 diameter from the center of the bolt. All hardness values are Rockwell C.

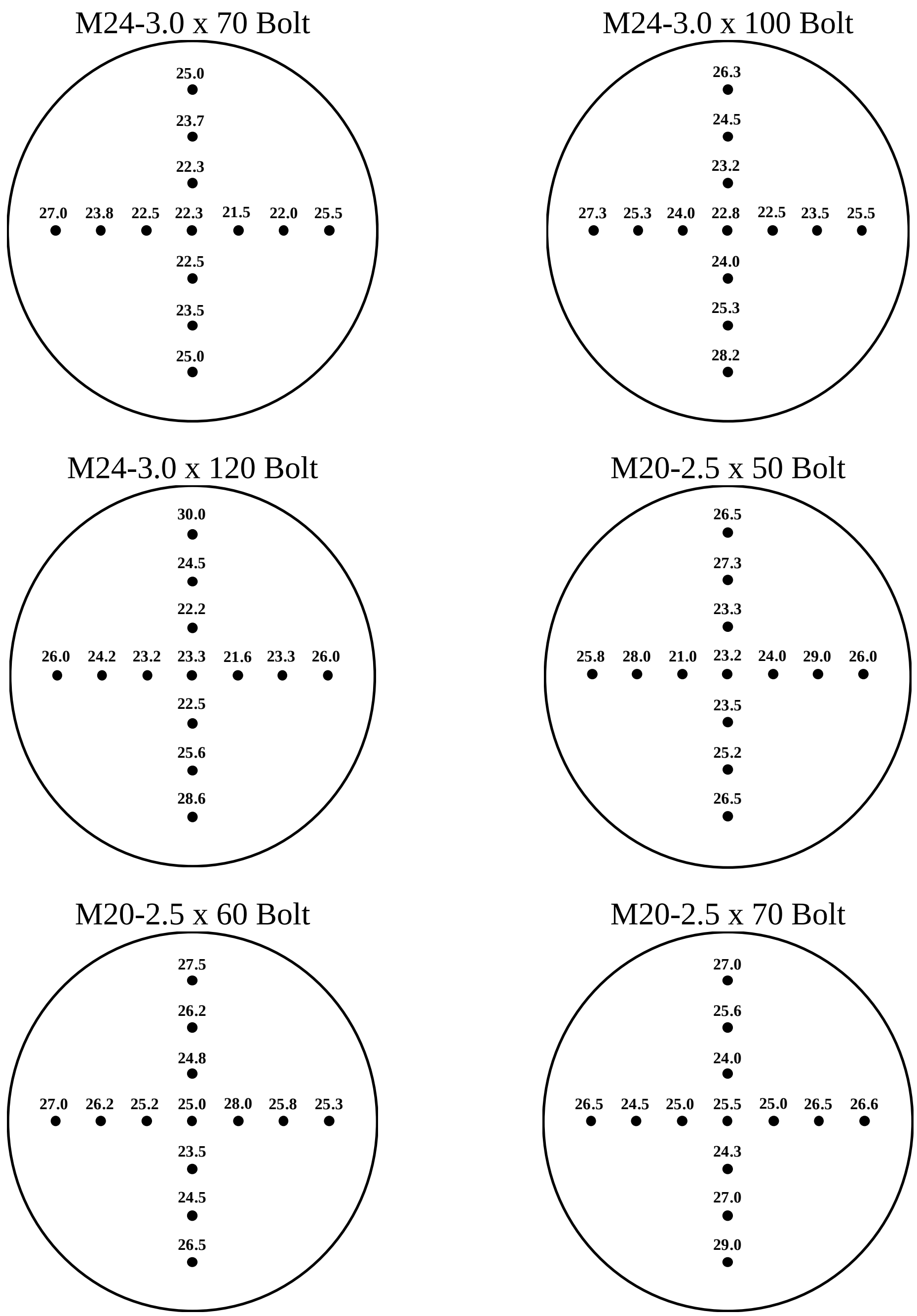


***Figure 3.1  $R_C$ Hardness Test Values for M24 and M20 A325M Bolts***

*Table 3.9 Average $R_C$ Hardness Test Results for M24 and M20 A325M Bolts and Nuts*

| Specimen | Mill 1/4 Diameter Hardness | Lab 1/4 Diameter Hardness |
|---|---|---|
| M24-3.0 X 70 Bolt | 23.1 | 23.3 |
| M24-3.0 X 100 Bolt | 27.2 | 24.7 |
| M24-3.0 X 120 Bolt | 28.7 | 24.4 |
| M24-3.0 6H GR10S Nut | 29.1 | 30.4 |
| M20-2.5 X 50 Bolt | 26.2 | 27.4 |
| M20-2.5 X 60 Bolt | 27.9 | 25.7 |
| M20-2.5 X 70 Bolt | 27.2 | 25.9 |
| M20-2.5 6H GR10S Nut | 29.6 | 29.5 |

ASTM specifies a minimum Rockwell Hardness of 24 and a maximum Rockwell Hardness of 34 for A325M bolts. For grade 10S nuts, ASTM A563M specifies a minimum Rockwell Hardness of 26 and a maximum Rockwell Hardness of 38 [3 and 4]. The average hardness values for both mill and lab tests indicate that the bolts and nuts meet these requirements.

### 3.2.3 Direct Tension Tests

The purpose of the tension tests of the full size bolts was to determine the tensile strengths of the bolt material and bolt-nut assembly. The direct tension tests were conducted in a Skidmore-Wilhelm Bolt Calibrator, as shown in Figure 3.2. Each bolt type was placed in the calibrator with the nut flush with the end of the bolt. During the test, the pressure in the calibrator was increased by hand-pumping hydraulic fluid into the calibrator until the bolt failed. The ultimate tensile strengths shown in Table 3.10 are the averages of three tests for basic bolt material strength. The range of test values is also indicated in this table. All bolts failed by fracturing in the threaded portion of the shank. Tests run by the manufacturer are included for comparison.

***Figure 3.2 Skidmore-Wilhelm Bolt Calibrator Used for Direct Tension Tests***

The results from the lab direct tension tests compare favorably with the tensile strengths from the mill reports, with the exception of the M24-3.0 x 70 and M20-3.0 x 70 bolt results. For these bolts, the tensile strengths determined through testing in the lab were significantly higher than the mill results. However, all recorded tensile strengths were greater than the ASTM specified minimum tensile strengths of 293 kN for M20 x 2.5 bolts and 203 kN for M20 x 2.5 bolts [3 and 4].

***Table 3.10 Ultimate Tensile Strength ($F_U$) of Bolts***

| **Bolt** | **Average Mill $F_U$ (kN)** | **Average Lab $F_U$ (kN)** |
|---|---|---|
| M24-3.0 X 70 | 330.0 ± 0.2 | 348.5 ± 3.0 |
| M24-3.0 X 100 | 348.5 ± 2.0 | 357.1 ± 3.0 |
| M24-3.0 X 120 | 358.3 ± 4.6 | 360.8 ± 4.5 |
| M20-2.5 X 50 | 230.8 ± 5.9 | 230.0 ± 3.0 |
| M20-2.5 X 60 | 236.4 ± 1.2 | 241.6 ± 3.0 |
| M20-2.5 X 70 | 238.3 ± 0.6 | 259.6 ± 3.0 |

### 3.3 TORQUE-TENSION-TURN TESTS

The stiffness and ductility of a bolt are affected by the grip length, number of threads within the grip, and the lubrication of the bolt-nut-washer assembly, as discussed in Chapter 2. In order to test each bolt at the maximum and minimum possible grip length, two grip conditions were used: nut flush with the end of the bolt and nut 3 turns from the end of the threads near the shank. The 3 turns grip condition was set as the minimum grip length to ensure that during a test to failure, there was adequate thread length to turn the nut to fail the bolt.

### 3.3.1 Bolt Matrix

The bolt matrix for the torque-tension-turn test is shown in Table 3.11. All testing was performed using hand wrenches to tighten the fasteners. The flush grip condition indicates that the bolt was tested with the nut flush with the end of the bolt, as displayed in Figure 3.3. The 3 turns grip condition indicates the bolt was tested with the nut 3 turns back from the position when the nut cannot be rotated at the end of the threads. This minimum grip length condition is displayed in Figure 3.4.

***Table 3.11  Torque-Tension-Turns Bolt Test Matrix***

| Diameter (mm) | Length (mm) | Grip | Grip Length (mm) | Condition | # |
|---|---|---|---|---|---|
| 24 | 70 | Flush | 46 | Lubricated | 3 |
| | 70 | Flush | 46 | Weathered | 3 |
| | 100 | 3 Turns | 63 | Lubricated | 3 |
| | 100 | 3 Turns | 63 | Weathered | 3 |
| | 100 | Flush | 76 | Lubricated | 3 |
| | 100 | Flush | 76 | Weathered | 3 |
| | 120 | 3 Turns | 75 | Lubricated | 3 |
| | 120 | 3 Turns | 75 | Weathered | 3 |
| | 120 | Flush | 96 | Lubricated | 3 |
| | 120 | Flush | 96 | Weathered | 3 |
| 20 | 50 | Flush | 30 | Lubricated | 3 |
| | 50 | Flush | 30 | Weathered | 3 |
| | 60 | Flush | 39 | Lubricated | 3 |
| | 60 | Flush | 39 | Weathered | 3 |
| | 70 | Flush | 50 | Lubricated | 3 |
| | 70 | Flush | 50 | Weathered | 3 |

*Figure 3.3  Example of Flush Grip for a 24 mm x 70 mm Bolt*

*Figure 3.4  Example of 3 Turns Grip for a 24 mm x 70 mm Bolt*

Two bolt conditions are listed in the torque-tension-turn bolt test matrix: lubricated and weathered. The lubricated condition denotes that the bolts, nuts, and washers were tested as received from the producer. The weathered condition denotes that the bolts, nuts, and washers were dipped in water and dried in air each of the two days prior to testing.

### 3.3.2 Load Cell - Solid Plate System

A test setup was built along with an automated data acquisition system to perform the torque-tension-turn tests. The test setup is shown in Figure 3.5. A flat shear type 445 kN (100 kip) load cell was mounted onto a 50.8 mm thick milled steel plate. A 101.6 mm diameter section at the center of the steel plate was bored down to a 25.4 mm thickness. A 26 mm diameter hole was drilled in the center of the borehole to accommodate the shank of the bolt. The bolt, nut and washer were installed into the load cell - flat plate setup. A threaded insert in the load cell permitted length adjustment so that both 24 mm x 120 mm flush (96 mm grip) and 3 turns (75 mm grip) conditions could be tested. A long socket extension was used which went from the installation wrench (a) supported by two bearings (b) to a 1627 N-m (1200 ft-lb) torque load cell and turn counter (c) with electronic output, through a final bearing for alignment, to a torque multiplier (d) to reduce the input torque required (e). The connection between the load cell (f) and the flat plate (g) is shown with more detail in Figures 3.6 and 3.7.

***Figure 3.5   Side View of Load Cell - Flat Plate System***

***Figure 3.6  Front View of Load Cell - Flat Plate System***

*Figure 3.7   Rear View of Load Cell - Flat Plate System*

### 3.3.3 Load Cell Box System

To accommodate shorter bolts, the test setup was altered to allow for grip lengths ranging from 96 mm to 46 mm. The load cell box system is displayed is Figure 3.8. This setup provided a relatively stiff fixture. The 24 mm x 120 mm flush (96 mm grip) and 3 turns (75 mm grip) were tested in this test setup to allow for comparison with Load Cell - Solid Plate System results. Two stiff steel plates were placed in between the load cell and the original mounting plate to provide 252 mm of clear space. The upper 91 mm x 252 mm plate was bolted into the top three holes of the load cell mounting pattern, while the lower 75 mm x 360 mm plate was bolted into the lower 3 holes of the mounting pattern to allow for a vertical interior clearance of 103 mm. A special apparatus was machined to turn into the 70 mm (2.75 in) threaded core of the load cell, as shown in Figure 3.8. The opposite end of the apparatus was designed to accept a small 75 mm diameter threaded insert containing the fixed bolt head, as shown in Figures 3.9 and 3.10. To test the limiting grip length of this setup (46 mm), the thickness of the bolted portion of the insert was minimized to 12 mm.

***Figure 3.8 Load Cell Box System***

***Figure 3.9  Grip Length Adjustment Apparatus for Load Cell Box System***

***Figure 3.10  Top View of Bolt Head Mounting Insert***

***Figure 3.11 Side View of Bolt Head Mounting Insert***

### 3.3.4 Short Grip Skidmore Test Setup

The short grip lengths of the 20 mm x 60 mm and the 20 mm x 50 mm bolts could no be tested in either of the load cell test setups. A short grip Skidmore-Wilhelm bolt calibrator (MS Model) was used to test these bolts. The Skidmore was substituted into the setup in place of the load cell box, as shown in Figure 3.12. A pressure transducer was connected to the bolt calibrator to allow for direct computer readings of the tensile load.

*Figure 3.12  Short Grip Skidmore Test Setup*

### 3.3.5  Test Procedure

The scanning capabilities of the data acquisition system enabled the simultaneous recording of tension, torque, and turns using a personal computer. After the fastener assembly was hand tightened into position, the system was zeroed and set into recording mode.  A manual wrench was then used to tighten the bolt.  Each test was terminated when the bolt failed or when the number of turns exceeded the recording limit of the system (2.5 turns from the starting position).  The same procedure was used in all torque-tension-turn tests.

## 3.4 TxDOT Tests

Three replicate rotational capacity tests were performed on each set of fasteners in the torque-tension-turn test matrix. The rotational capacity test was slightly modified from the standard test in order to provide additional information. An air-powered nut runner and torque multiplier were used to turn the nut in $60^{o}$ increments in a Skidmore-Wilhelm bolt calibrator from an assumed snug tension equal to 10 % of the minimum bolt tensile strength until failure. The tension and nut rotation were recorded at each increment. The M Model Skidmore was used to test all bolts except for the 50 mm and 60 mm lengths of the 20 mm bolts. As with the torque-tension-turn tests, the MS Model Skidmore was used to test these bolts.

## 3.5 Solid Plate Tests

### 3.5.1 Bolt Test Matrix

The bolt matrix for the solid plate tension-turn test is shown in Table 3.12. These bolts were tested in A572 Grade 50 material plates machined to the various grip lengths, with a hole diameter equal to the bolt diameter plus 2 mm.

***Table 3.12  Solid Plate Test Bolt Matrix***

| Diameter (mm) | Length (mm) | Grip | Grip Length (mm) | Condition | # |
|---|---|---|---|---|---|
| 24 | 70 | 3 Turns | 32 | Lubricated | 3 |
| | 70 | Flush | 46 | Lubricated | 3 |
| | 120 | 3 Turns | 75 | Lubricated | 3 |
| | 120 | Flush | 96 | Lubricated | 3 |
| 20 | 50 | Flush | 30 | Lubricated | 3 |
| | 70 | 3 Turns | 37 | Lubricated | 3 |
| | 70 | Flush | 50 | Lubricated | 3 |

### 3.5.2  Determining Tension-Elongation Relationship

The first step in the solid plate test was to produce tension vs. elongation calibration curves for each bolt and grip length to be examined. The tension-elongation relationships are used to determine the tension in the solid plate tests. These curves were developed by tightening each bolt in a Skidmore-Wilhelm bolt calibrator and measuring bolt elongation and tension at approximately every 30$^o$ of nut rotation, until the bolt failed. All calibration test bolts were end drilled to allow for seating of dial gauge metal points at each end. The elongation of each bolt was measured with a C frame mounted 0.0001 in dial gauge, as shown in Figure 3.13.

*Figure 3.13  C Frame Dial Gauge*

Three tension-elongation calibrations were performed on each bolt grip length condition.  Linear regression was used to calculate the slope of the elastic region of the tension vs. elongation curves.  The average of the slopes from three tension-elongation tests was taken as the elastic relationship.  The average tension per elongation slope was multiplied by the elongation values in the elongation vs. rotation data to develop the elastic portion of the tension vs. rotation relationship for each bolt.

### 3.5.3  Determining Elongation-Rotation Relationship

Each bolt was tightened to failure in a solid plate with a thickness equal to the grip length.  The elongation was measured at $7.5^{o}$ nut rotation increments in the elastic region.  Larger rotation increments were used as the elongation-rotation relationship became more linear.  The solid plate test setup is displayed in Figure 3.14.  A summary of the test setups used for each bolt grip condition is presented in Table 3.13.

***Figure 3.14  Solid Plate Test Setup***

*Table 3.13 Summary of Bolt Tests*

| Dia. (mm) | Length (mm) | Grip | L. C. - Solid Plate | L. C. Box | Short Grip Skidmore | TxDOT | Solid Plate |
|---|---|---|---|---|---|---|---|
| 24 | 70 | 3 Turns | | | | X | X |
| | 70 | Flush | | X | | X | X |
| | 100 | 3 Turns | | X | | X | |
| | 100 | Flush | | X | | X | |
| | 120 | 3 Turns | X | X | | X | X |
| | 120 | Flush | X | X | | X | X |
| 20 | 50 | Flush | | | X | X | X |
| | 60 | Flush | | | X | X | |
| | 70 | 3 Turns | | | | | X |
| | 70 | Flush | | X | | X | X |

# CHAPTER 4

# DATA PRESENTATION

## 4.1 INTRODUCTION

The results of the torque-tension-turn tests and the tension-turn tests were analyzed with respect to the current installation requirements of the AASHTO turn-of-the-nut procedure and rotational capacity test. Two different snug conditions and the output from test setups of differing stiffness were analyzed and utilized to best determine the installation requirements for the A325M metric bolts. Alternate installation requirements are presented when the current AASHTO requirements for inch bolts were not satisfactory for the A325M metric bolts. Final recommendations for changes to the current bolt specification are given in Chapter 5.

## 4.2 SNUG CONDITION

The AASHTO Specification states the a snug tight condition "may be attained by a few impacts of an impact wrench or the full effort of a man using an ordinary spud wrench". This definition leaves no quantifiable value of snug in terms of fastener tension or torque. A man using an impact wrench could conceivably apply a much larger torque than a man using a spud wrench. The snug definition becomes more ambiguous when considering the variance of "full effort" from one man to another. However, the snug condition is very important to the effectiveness of the turn-of-the-nut method. The specified nut rotations to reach the required tension in the fastener are applied after the bolt has been tightened to a snug condition.

The previous research on inch bolts used a snug tension equal to 10% of the minimum specified tensile strength of the fastener to determine the nut rotation requirements [11]. For the A325M metric bolt research project, two snug tension conditions were examined: 10% of the minimum specified tensile strength (20.3 kN for the 20 mm bolts and 29.3 kN for the 24 mm bolts) and a fastener tension of 44.48 kN (10 kips). Figures 4.1 and 4.2 show the torque required to reach these snug tension conditions for each bolt tested in a torque-tension-turn test. These plots include data from different test setups ranging from load cell - solid plate to short grip Skidmore. As expected, the test setup did not influence the torque-tension relationship The data also includes bolts tested in the as received and weathered conditions. The removal of lubrication did not have any appreciable effect on the torque-tension relationship. The torque required for the 20 mm bolts was less than the torque required for the 24 mm bolts for both snug conditions.

The maximum torque a man can apply using an ordinary spud wrench was estimated to be 203 N-m (150 ft-lb). The torques required to produce the 10% of minimum specified tensile strength snug condition are representative of this 150 ft-lb maximum torque input. The maximum and minimum torques were 273 N-m (201 ft-lb) and 107 N-m (79 ft-lb), respectively.

The torques required to reach the 44.48 kN snug tension condition were significantly higher than the torques required to reach 10% of the minimum specified tensile strength. The 44.48 kN snug torques ranged from 210 N-m (155 ft-lb) and 343 N-m (253 ft-lb). All of these torques are above the estimated maximum torque input of 203 N-m (150 ft-lb). The 44.48 kN snug condition requires torques that are not plausible for a man with a spud wrench. However, this snug condition can be used to estimate the maximum snug when using an impact wrench.

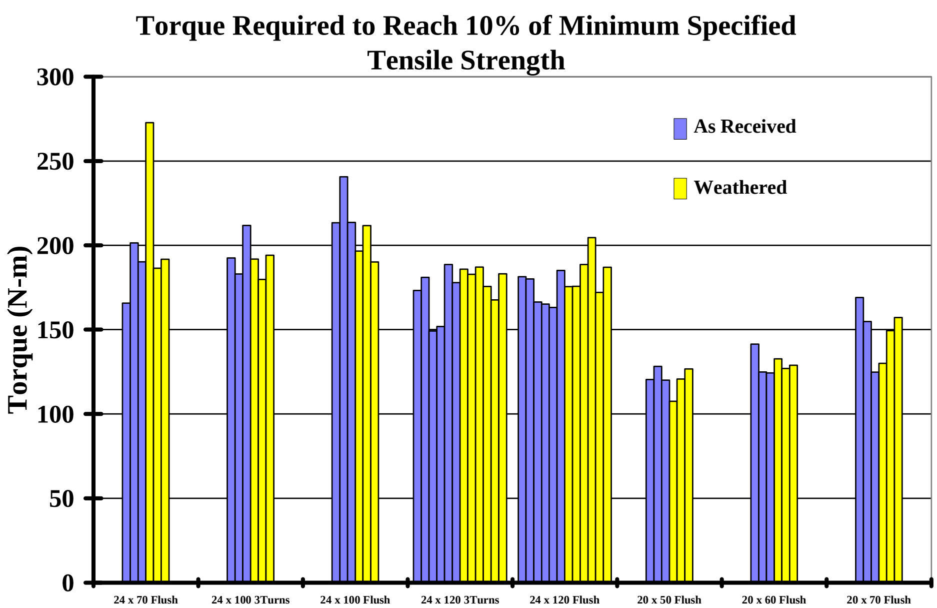


***Figure 4.1 Torque Required to Reach 10% of Minimum Specified Tensile Strength***

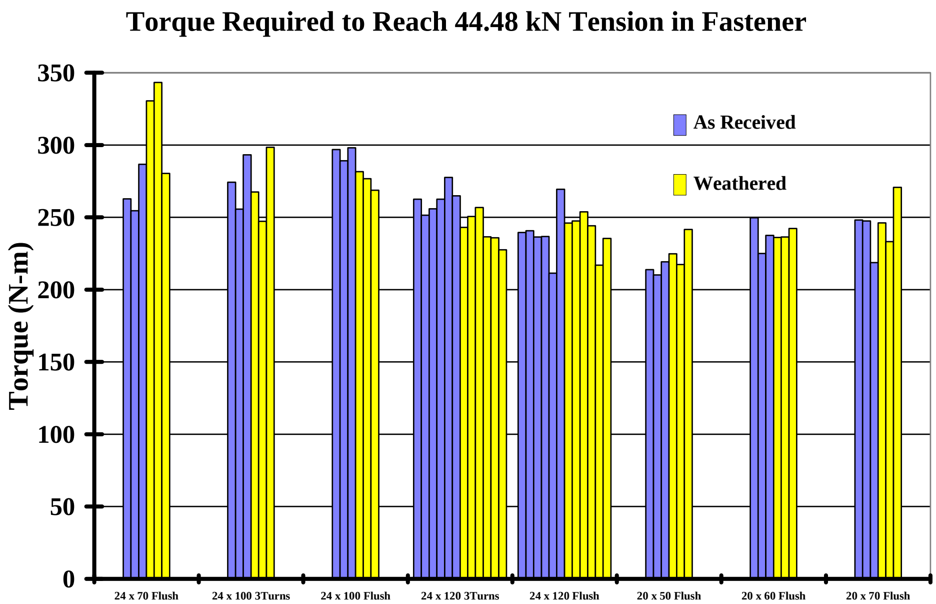


***Figure 4.2 Torque Required to Reach 44.48 kN Tension in Fastener***

In addition, the 44.48 snug tension is more likely to be on the linear-elastic portion of the tension-turn curve. Figure 4.3 shows a graph of the initial part of a tension-turn load curve up to the minimum specified fastener tension for a 20 mm x 70 mm lubricated flush grip bolt in the load cell box test setup. The graph clearly shows that the 44.48 kN snug point lies on the linear elastic portion of the loading curve. The 20.3 kN snug point occurs before the curve becomes linear. Figure 4.4 indicates similar results for the same type of bolt tested in a solid plate. In this case, the 20.3 kN point is closer to the start of the linear portion of the tension-turn curve. These results are typical for all bolts tested in the torque-tension-turn and solid plate tests. The 44.48 kN snug tension condition provides a more uniform starting point for examining the relative behavior of bolts in the various test setups because the point is on the linear-elastic portion of the curve.

Using a snug point that occurs before the curve becomes linear would make determination of the influence of the test setups on bolt behavior difficult. The amount of “play” or initial looseness in the test setup and the bolt-nut-washer-assembly at the start of loading varies from test to test and setup to setup. As a result, the length of the curve before the linear portion is different for each bolt tested.

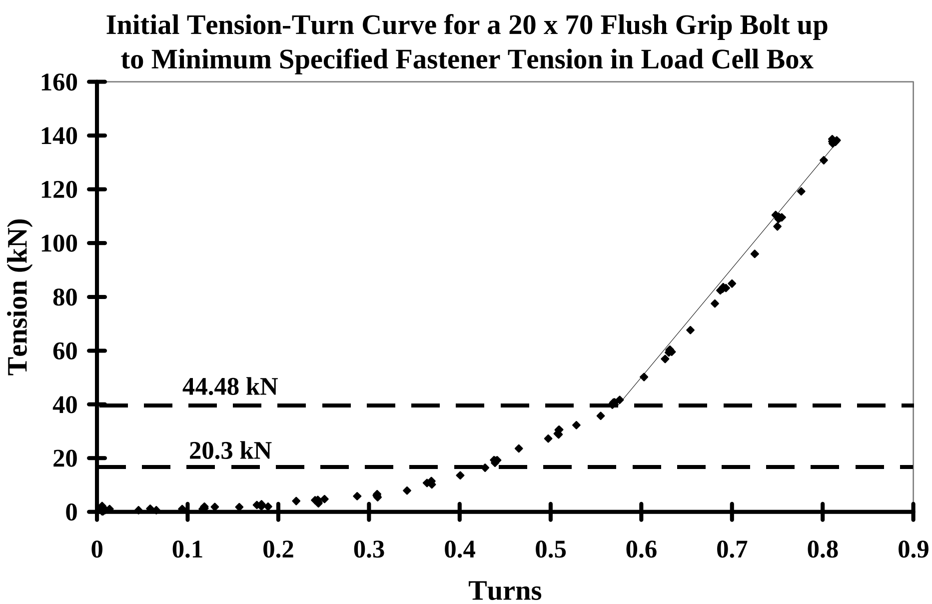


***Figure 4.3 Initial Tension-Turn Curve for a 20 x 70 Flush Grip Bolt up to Minimum Specified Fastener Tension in Load Cell Box***

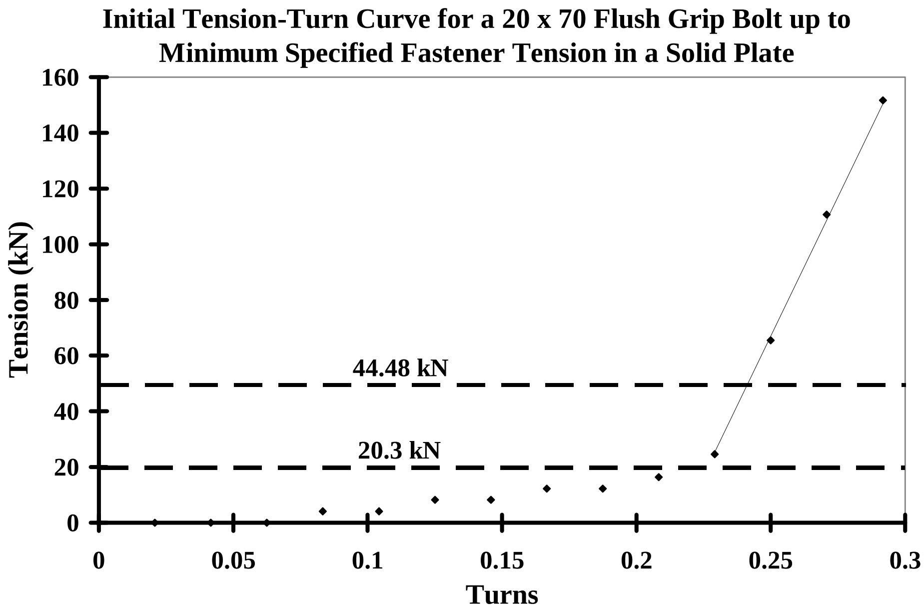


***Figure 4.4 Initial Tension-Turn Curve for a 20 x 70 Flush Grip Bolt up to Minimum Specified Fastener Tension in a Solid Plate***

In this research, the ultimate rotational capacity of each bolt was measured from the 44.48 kN snug. This tension represents the estimated maximum snug condition in the field. Conversely, the nut rotations required to reach the minimum specified fastener tension were measured from the 10% of minimum specified tensile strength snug condition. This condition represents the estimated minimum snug condition in the field. The 44.48 kN snug condition was also used to compare the initial stiffness of each bolt in the different test setups.

## 4.3 EFFECT OF WEATHERING UPON LUBRICATION PERFORMANCE

The results of all testing indicated no significant difference in bolt behavior between those bolts that were tested in the as received condition and those that were weathered in the laboratory before testing. Table 4.1 compares the average nut factors for the as received and weathered bolts tested in the torque-tension-turn tests. The nut factors indicate that the installation torques for each of the lubrication conditions were remarkably similar from the snug point (as presented in Figures 4.1 and 4.2) up to and including the maximum torque in the

***Table 4.1 Average Nut Factors for Torque-Tension-Turn Tests***

| **Diameter** | **Length** | **Grip** | **Average Nut Factor** | |
|---|---|---|---|---|
| **(mm)** | **(mm)** | | **As Received** | **Weathered** |
| 24 | 70 | Flush | 0.225 | 0.208 |
| | 100 | 3 Turns | 0.212 | 0.200 |
| | 100 | Flush | 0.211 | 0.211 |
| | 120 | 3 Turns | 0.206 | 0.203 |
| | 120 | Flush | 0.206 | 0.207 |
| 20 | 50 | Flush | 0.200 | 0.228 |
| | 60 | Flush | 0.241 | 0.251 |
| | 70 | Flush | 0.224 | 0.240 |

test. In addition, there was no significant difference in ductility as measured by turns to failure. Table 4.2 compares the average turns to failure in the torque-tension-turn tests for each lubrication condition. The turns to failure were measured from a snug tension equal to 44.48 kN. The results indicate that the lubricant supplied on the as received fastener was not significantly degraded by the simulated weathering done in the laboratory.

***Table 4.2 Average Turns to Failure for Torque-Tension-Turn Tests***

| Diameter | Length | Grip | Test Setup | Average Turns to Failure | |
|---|---|---|---|---|---|
| (mm) | (mm) | | | As Received | Weathered |
| 24 | 70 | Flush | Load Cell Box | 1.80 | 1.92 |
| | 100 | 3 Turns | Load Cell Box | 1.26 | 1.28 |
| | 100 | Flush | Load Cell Box | 1.69 | 1.62 |
| | 120 | 3 Turns | Load Cell Box | 1.33 | 1.38 |
| | 120 | 3 Turns | L. C.- Solid Plate | 1.42 | 1.38 |
| | 120 | Flush | Load Cell Box | 2.20 | 2.22 |
| | 120 | Flush | L. C.- Solid Plate | 2.22 | 2.12 |
| 20 | 50 | Flush | Short Grip Skidmore | 2.19 | 2.06 |
| | 60 | Flush | Short Grip Skidmore | 1.82 | 1.76 |
| | 70 | Flush | Load Cell Box | 1.76 | 1.78 |

## 4.4 Bolt Performance in Different Test Setups

Figures 4.5 through 4.9 graphically contrast the performance of bolts tested in the solid plate setup with the results of replicate tests in other test setups. The plots display the effects of the wide spectrum of test setup stiffnesses upon the rotational performance of the bolts. In each case, the bolt tested in the solid plate had the highest initial stiffness and the lowest ductility, or ultimate rotational capacity. The bolts tested in the TxDOT Skidmore test setups had the lowest initial stiffness, with the exception of the 24 mm x 70 mm and the 20 mm x 50 mm bolts. These bolts had essentially had essentially the same stiffness in the load cell box and the TxDOT Skidmore test setups.

The stiffness of a multiple ply connection is expected to fall between the hydraulic bolt calibrator and solid plate extremes. The results from the test setup with the lowest stiffness were used to establish nut rotation requirements because a bolt tested in this setup requires the highest number of turns to reach a specified tension. Similarly, the data from the solid plate test setup was used to check ultimate rotational capacity limitations because the reduced rotational ductility of a bolt tested in this setup results in the lowest number of turns to failure.

The inelastic portion of the tension-turn curve was found to be independent of the test setup. The 24 x 120 flush grip bolt tension-turn curves in Figure 4.7 illustrate the fact that the nut rotations in the inelastic range of the solid plate and TxDOT tests are approximately equal (1.54 turns and 1.56 turns), despite large differences in initial stiffness. The inelastic behavior of the bolt is not a function of the type of test setup.

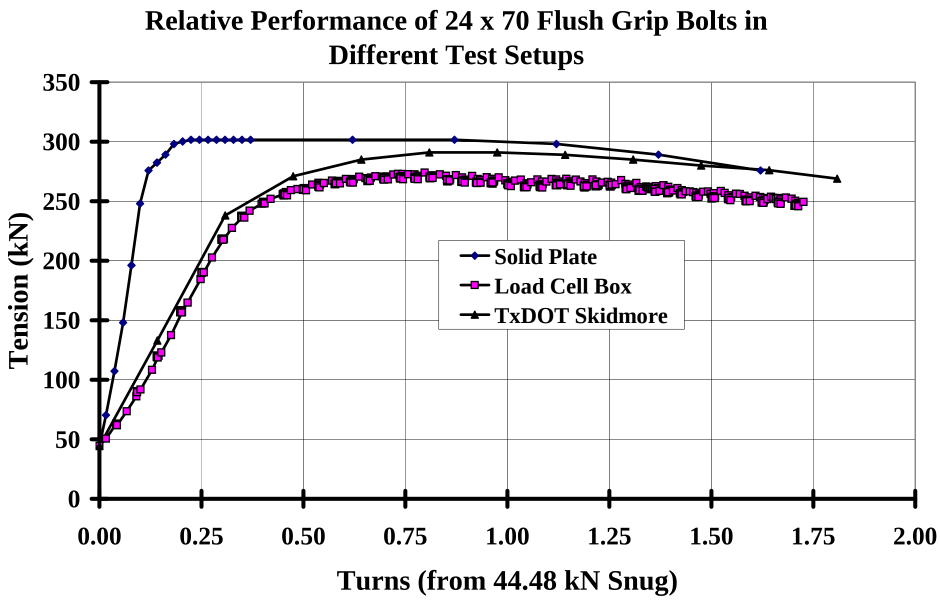


*Figure 4.5  Relative Performance of 24 x 70 Flush Grip Bolts in Different Test Setups*

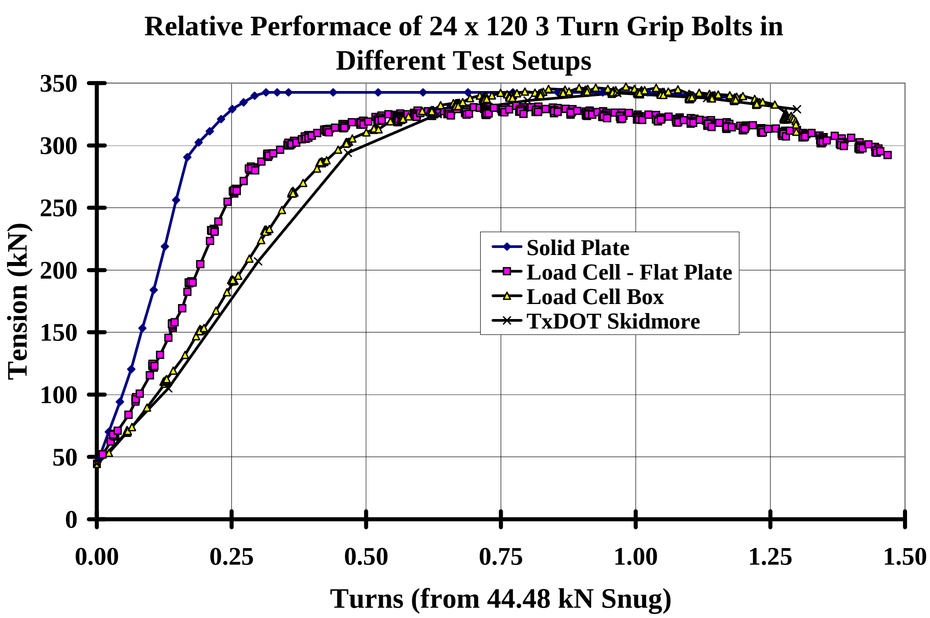


*Figure 4.6  Relative Performance of 24 x 120 3 Turn Grip Bolts in Different Test Setups*

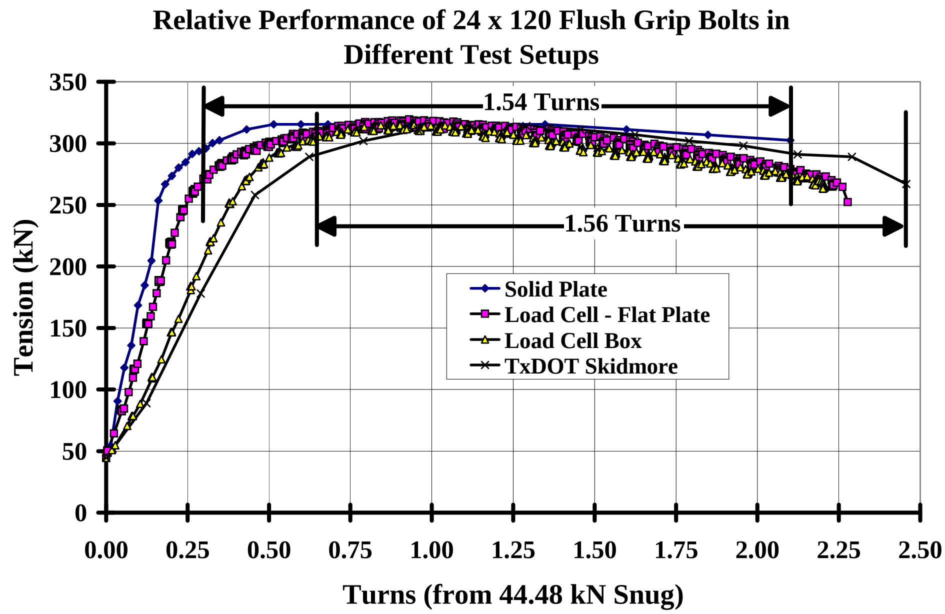


*Figure 4.7 Relative Performance of 24 x 120 Flush Grip Bolts in Different Test Setups*

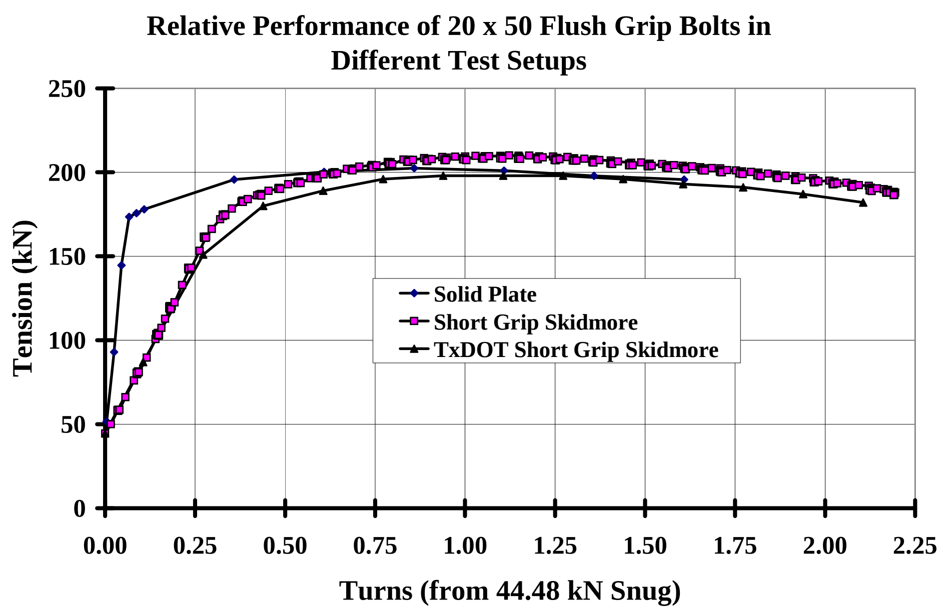


*Figure 4.8 Relative Performance of 20 x 50 Flush Grip Bolts in Different Test Setups*

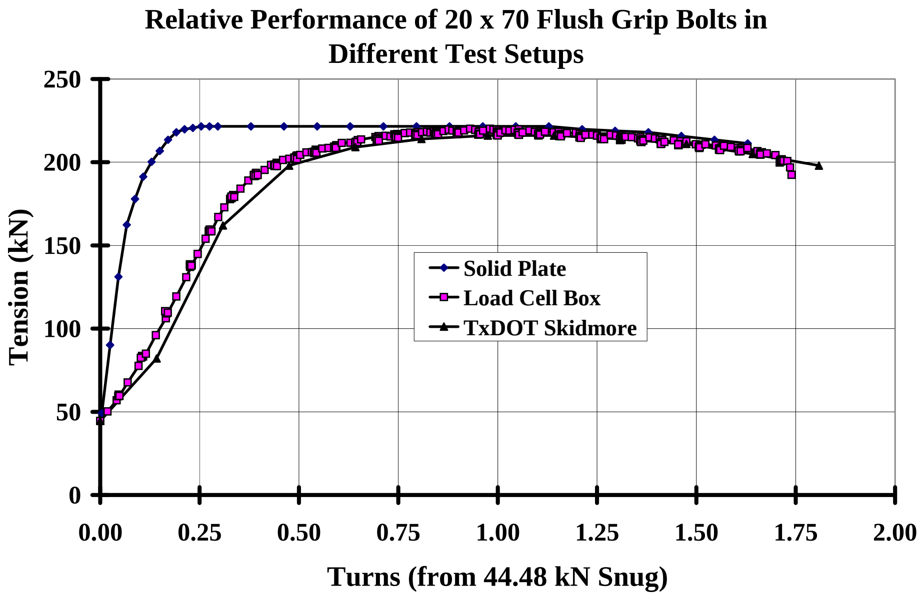


***Figure 4.9 Relative Performance of 20 x 70 Flush Grip Bolts in Different Test Setups***

## 4.5 Rotational Stiffness

The relationship between tension and nut rotations from a snug tension of 44.48 kN to the minimum specified fastener tension for a given bolt is reasonably linear. Therefore, the "rotational stiffness" of any bolt can be calculated by using linear regression to determine the slope of the tension-turn curve between these points. The slope of the linear portion of the tension-turn curve is defined by the following equation,

$$\text{Rotational Stiffness} = \Delta T / \Delta N \qquad (4.1)$$

where $\Delta T$ is the change in fastener tension and $\Delta N$ is the change in nut rotation, as depicted in Figure 4.10.

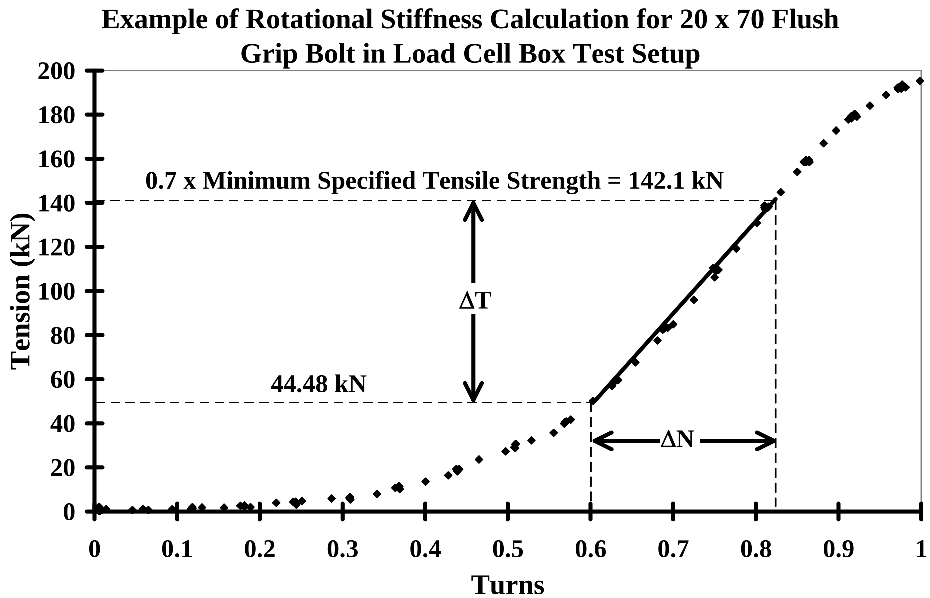


***Figure 4.10  Example of Rotational Stiffness Calculation for 20 x 70 Flush Grip Bolt in Load Cell Box Test Setup***

The rotational stiffnesses for bolts tested in the torque-tension-turn tests are compared with the solid plate test results in Figures 4.11 and 4.13. For the 50 mm and 70 mm bolts (both 20 mm and 24 mm diameters), the rotational stiffnesses were 4 to 5 times higher in the solid plate than in the short grip Skidmore and load cell box tests. For the 24 mm x 120 mm bolts tested in the solid plates, the rotational stiffnesses were approximately 2.2 times larger than the stiffnesses from the load cell box test setup, and 1.5 time times larger than stiffnesses from the load cell - flat plate test setup. As expected, the graphs also indicate an increase in rotational stiffness for shorter grip lengths in the solid plate tests.

Figures 4.12 and 4.14 show the influence of grip length on rotational stiffness in the torque-tension-turn tests. As with the solid plate results, the load cell - solid plate, load cell box, and short grip Skidmore test results indicate an inverse relationship between rotational stiffness and grip length. It should be noted that the TxDOT Skidmore results are not included because the linear portions of these curves do not contain enough points to accurately define a slope.

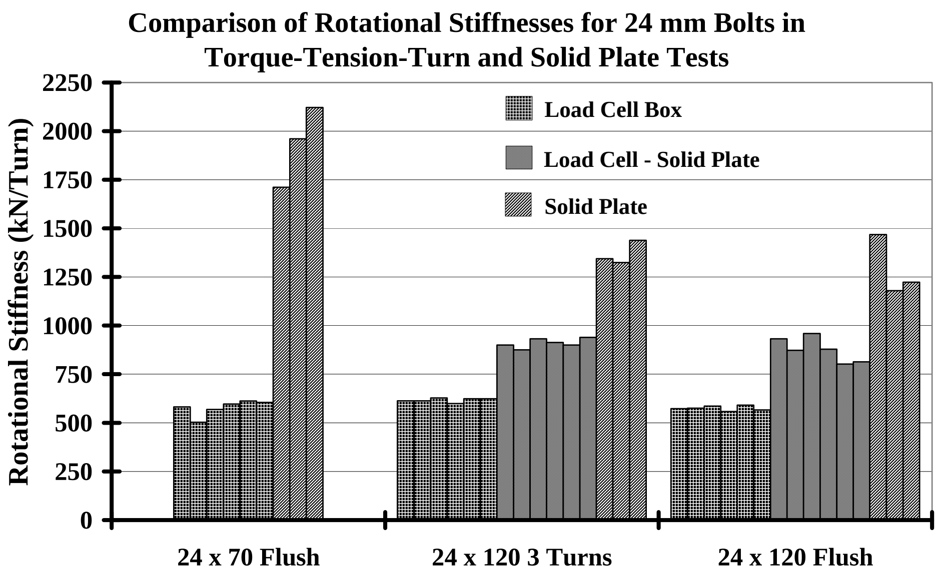


***Figure 4.11 Comparison of Rotational Stiffnesses for 24 mm Bolts in Torque-Tension-Turn and Solid Plate Tests***

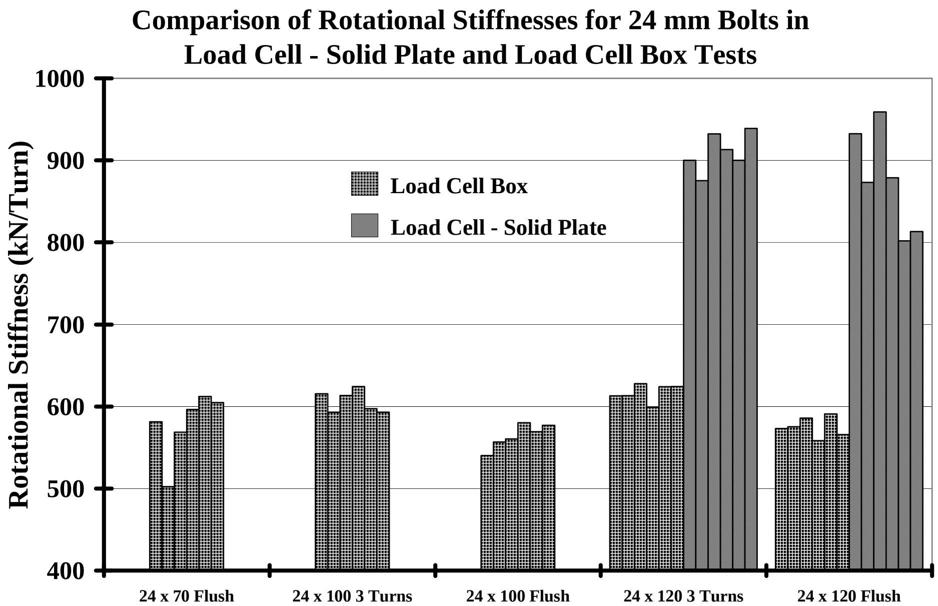


*Figure 4.12 Comparison of Rotational Stiffnesses for 24 mm Bolts in Load Cell - Solid Plate and Load Cell Box Tests*

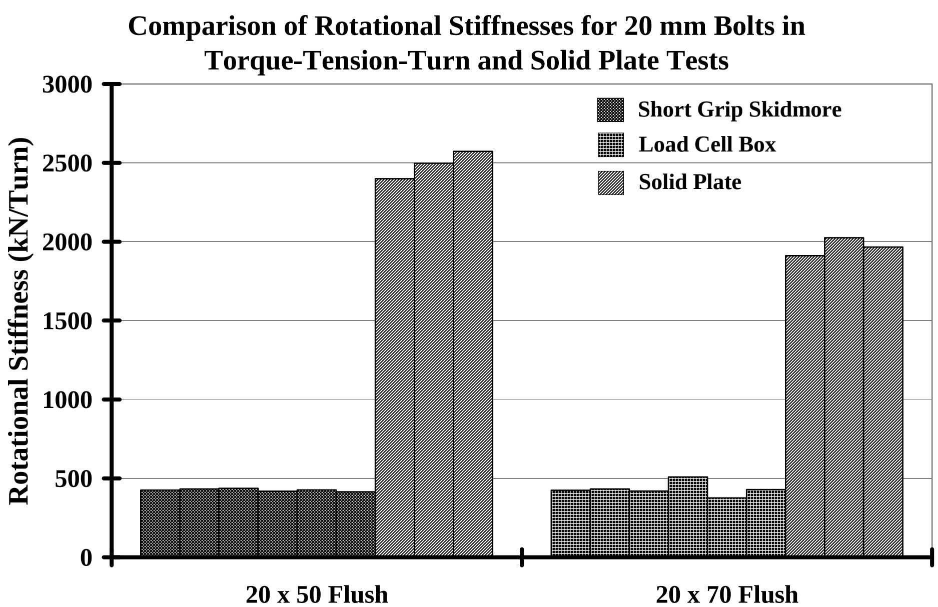


*Figure 4.13 Comparison of Rotational Stiffnesses for 20 mm Bolts in Torque-Tension-Turn and Solid Plate Tests*

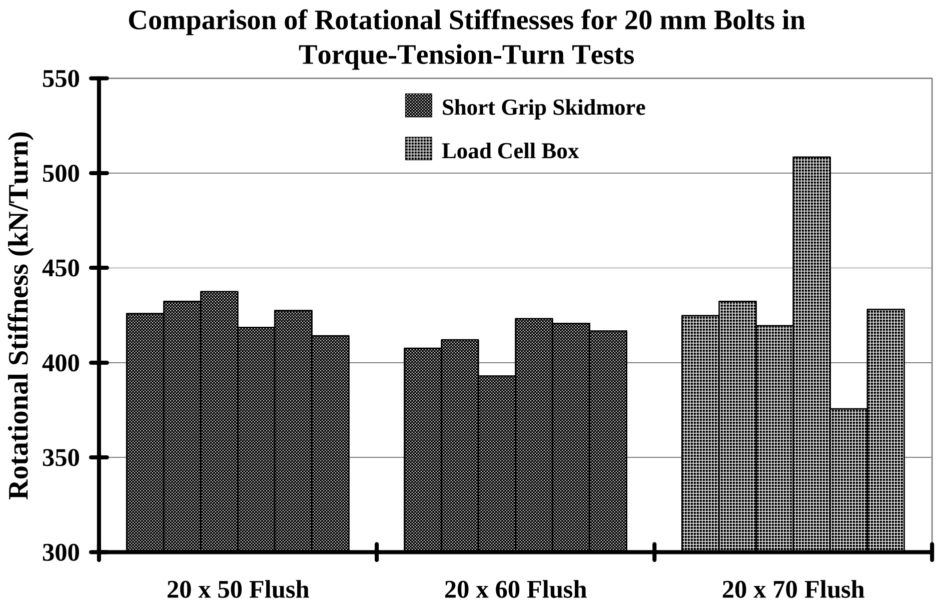


***Figure 4.14 Comparison of Rotational Stiffnesses for 20 mm Bolts in Torque-Tension-Turn Tests***

## 4.6 NUT ROTATION

The number of nut rotations required to reach the minimum specified fastener tension from a snug tension equal to 10% of the minimum specified tensile strength was calculated for every bolt tested. The snug tension was equal to 20.3 kN for the 20 mm bolts and 29.3 kN for the 24 mm bolts. As stated previously, the bolts tested in the lower stiffness test setups required the highest number of nut rotations. The nut rotation requirements for the load cell - flat plate, load cell box, short grip Skidmore, and TxDOT Skidmore tests are presented in Figures 4.15 through 4.22. In each graph, the nut rotation axis has $30^{o}$ degree gridline increments.

The 24 mm x 120 mm 3 turn and flush grip results (Figures 4.18 and 4.19) indicate that the required number of turns to reach the minimum specified fastener tension decreases as the stiffness of the test setup increases, as expected. The influence of test setup on the required nut rotations is minimal for the other results because the overall stiffnesses of the load cell box and Skidmore test setups examined in these cases are about the same.

A comparison of the required nut rotations for the two grip conditions for the 24 mm x 100 mm bolts (Figures 4.16 and 4.17) and the 24 mm x 120 mm bolts (Figures 4.18 and 4.19) shows that the 3 turns bolts required slightly less turns than the flush bolts. An examination of the required nut rotations for the 20 mm bolts (Figures 4.20 through 4.21) also indicates an increase in the required turns for longer grip lengths in the same test setup.

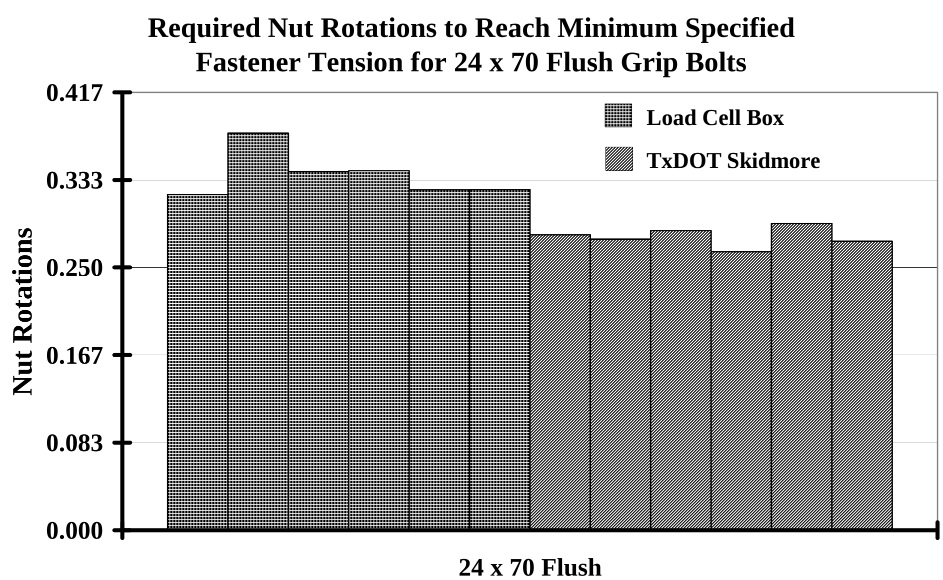


***Figure 4.15 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 70 Flush Grip Bolts***

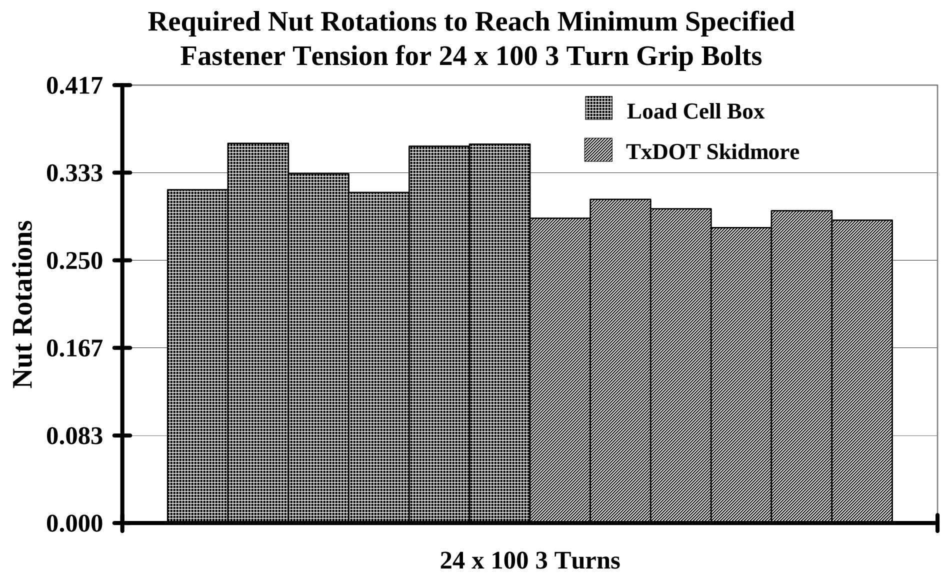


*Figure 4.16 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 100 3 Turn Grip Bolts*

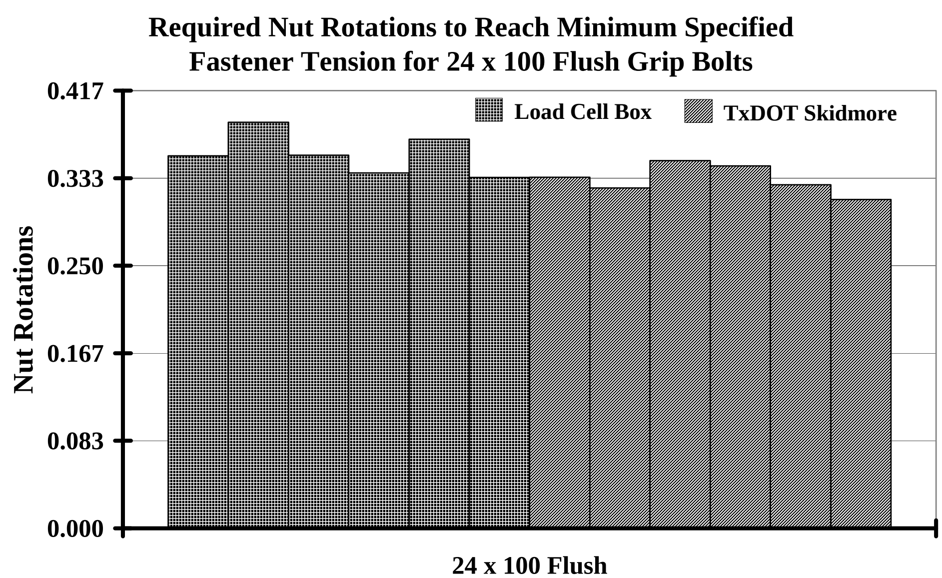


*Figure 4.17 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 100 Flush Grip Bolts*

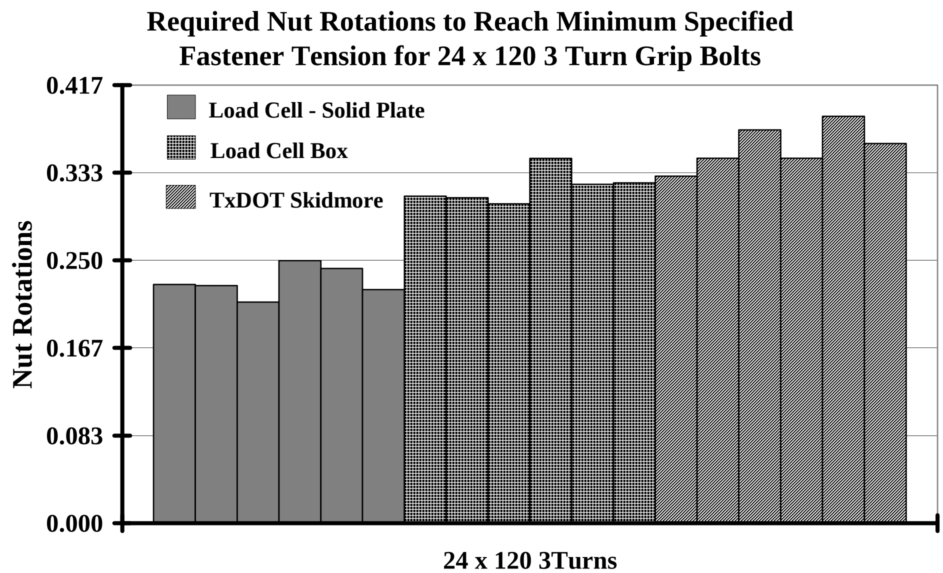


*Figure 4.18 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 120 3 Turn Grip Bolts*

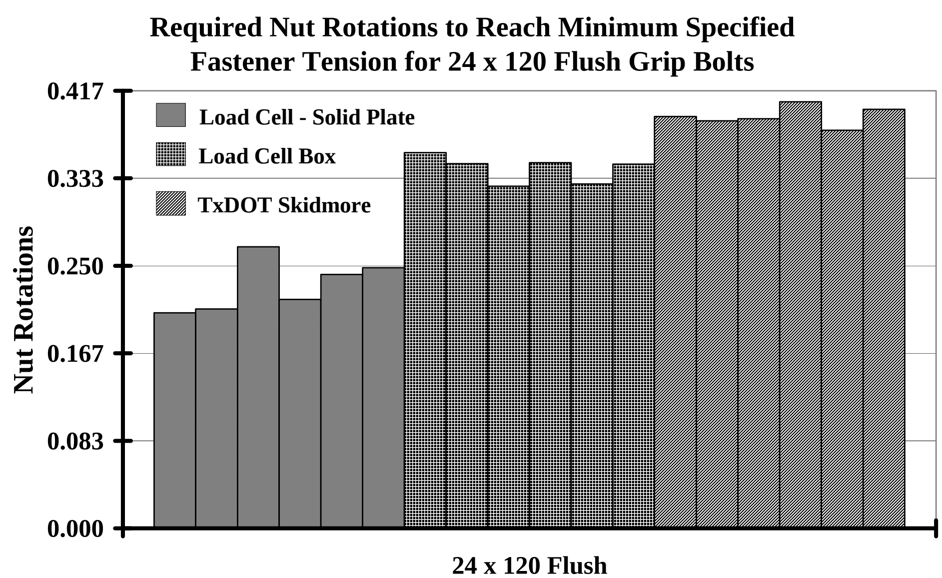


*Figure 4.19 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 120 Flush Grip Bolts*

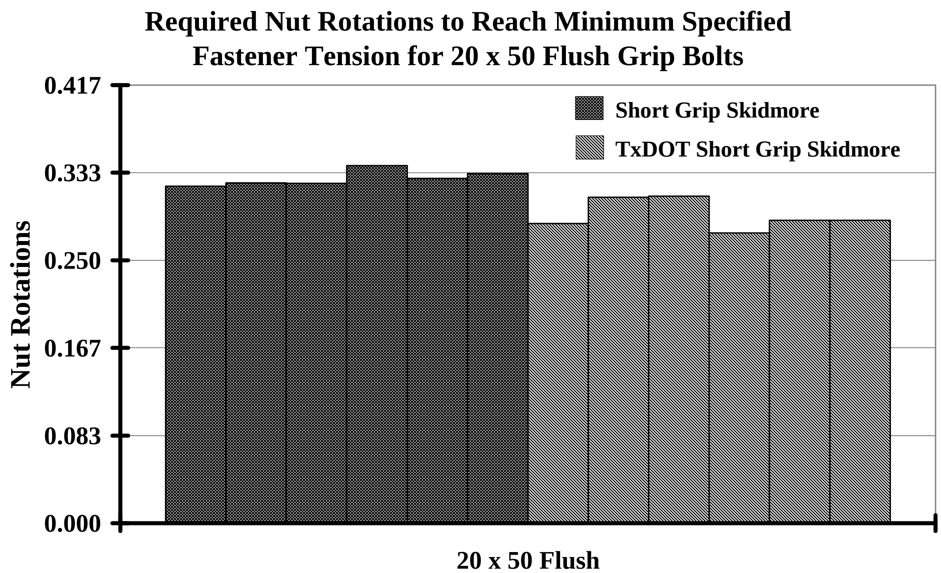


*Figure 4.20 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 20 x 50 Flush Grip Bolts*

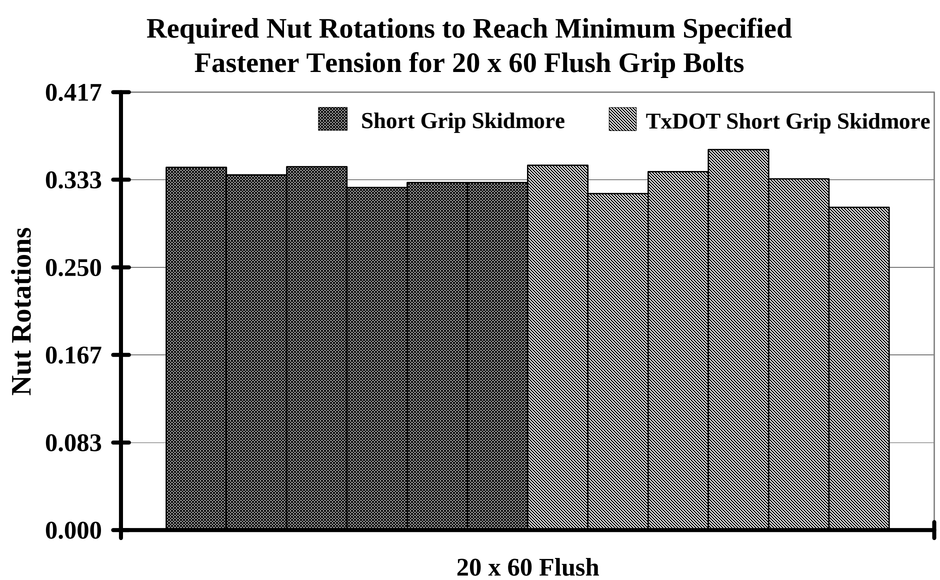


*Figure 4.21 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 20 x 60 Flush Grip Bolts*

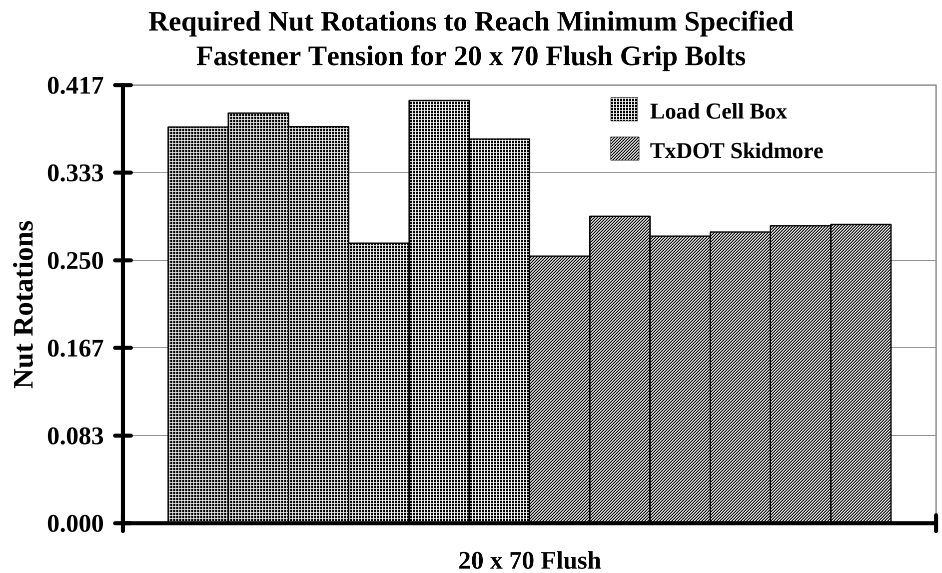


***Figure 4.22  Required Nut Rotations to Reach Minimum Specified Fastener Tension for 20 x 70 Flush Grip Bolts***

## 4.7 ULTIMATE NUT ROTATIONAL CAPACITY

The ultimate nut rotational capacity was determined in the stiffest test setup, the solid plate, which provides the least bolt ductility, or lowest number of turns to failure.  The values of rotational capacity in the solid plate test were determined using a 44.48 kN snug condition.  The number of turns to failure for each set of bolts tested in the solid plate setup are plotted in Figure 4.23.  The lowest rotational capacity recorded was 1.074 for one of the 20 mm x 70 mm 3 turn grip bolts.  This value is nearly 2/3 turn less than the rotational capacities for the same bolt with a flush grip condition.  The differences in rotational capacity shown in Figure 4.23 clearly indicate that reducing the grip length can significantly reduce ductility.

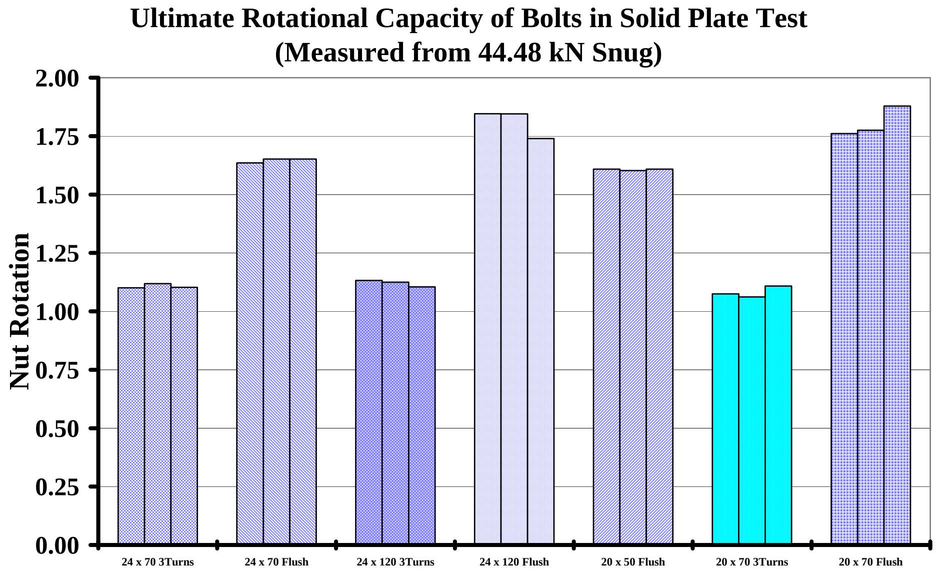


***Figure 4.23  Ultimate Rotational Capacity of Bolts in Solid Plate Test***

## 4.8 ROTATIONAL CAPACITY TEST REQUIREMENTS

### 4.8.1 Nut Factor / Maximum Torque

The relationship between torque and tension in the torque-tension-turn tests was found be linear, as shown in Figure 4.24. To analyze the performance of each bolt with respect to the rotational capacity test, the average nut factor was calculated each torque-tension-turn bolt test. The rotational capacity test does not allow for a nut factor greater than 0.25 at any point in the test for long bolts. Only 4 bolts, or 6.7% of the test matrix would fail to pass this test in the field. Figure 4.24 shows the average nut factors for all the torque-tension-turn tests. The average nut factor was equal to 0.21

For short bolts, where no tension readings are possible, the maximum allowable torque in the rotational capacity test is defined by the following equation,

$$\text{Max. Torque} = 0.25 \times 1.15 \times 0.70 \times \text{spec. } F_{Umin} \times \text{Dia.} \qquad (5)$$

This equation assumes that the maximum fastener tension is only 15% greater than the minimum specified fastener tension. The maximum torque exceeded the maximum allowable torque in 75% of the torque-tension-turn tests, as shown in Figure 4.26. In order to show the severity of the 15% assumption, the maximum tension in each of the torque-tension turn and TxDOT tests was divided by 70% of the actual tensile strength, which is significantly greater than the specified minimum tensile strength. These results are presented in Figures 4.27 and 4.28. The assumed 15% increase in fastener tension is very conservative. The majority of the bolts showed increases greater than 20%.

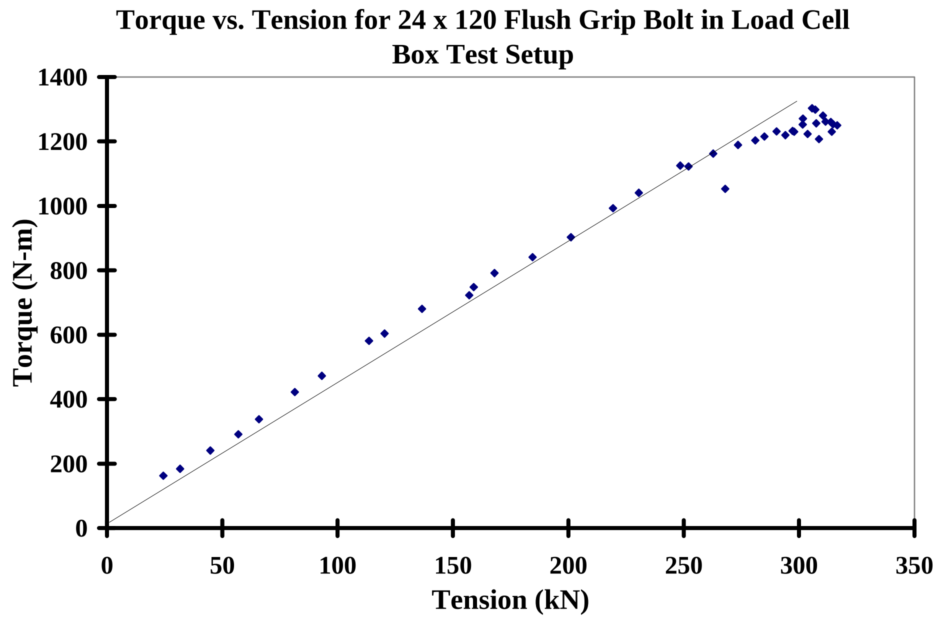


*Figure 4.24 Torque vs. Tension for 24 x 120 Flush Grip Bolt*

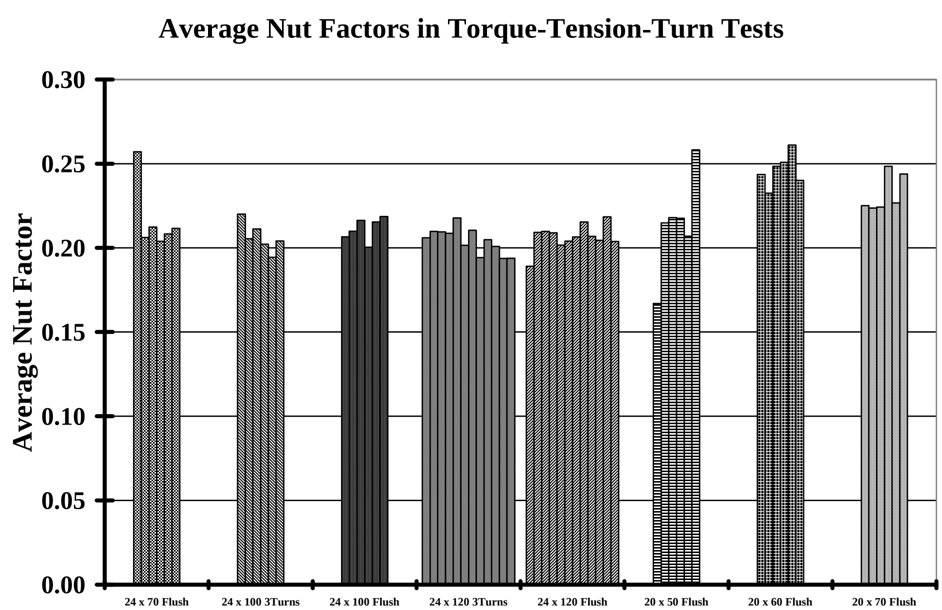


*Figure 4.25 Average Nut Factors in Torque-Tension-Turn Tests*

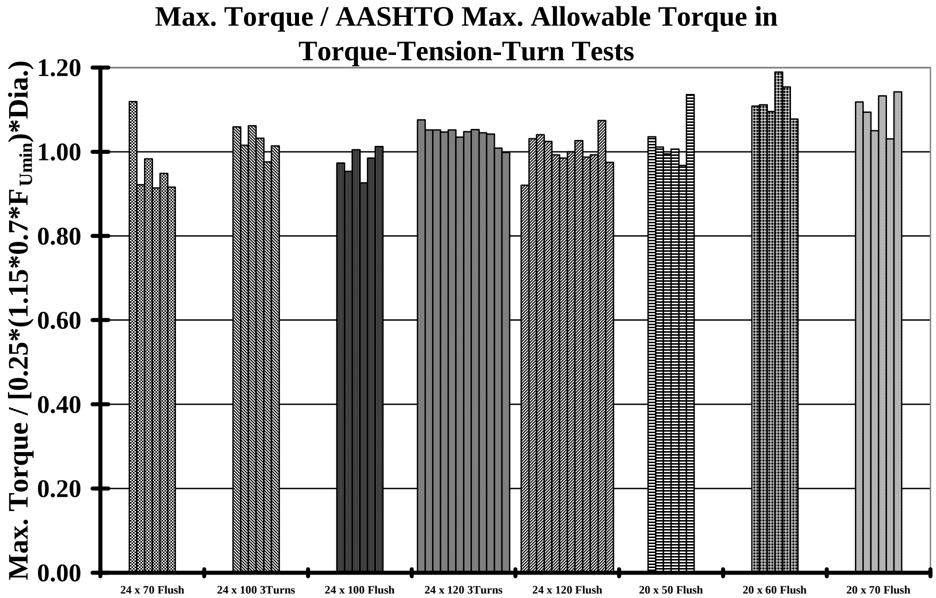


*Figure 4.26 Maximum Torque in Test / AASHTO Maximum Allowable Torque*

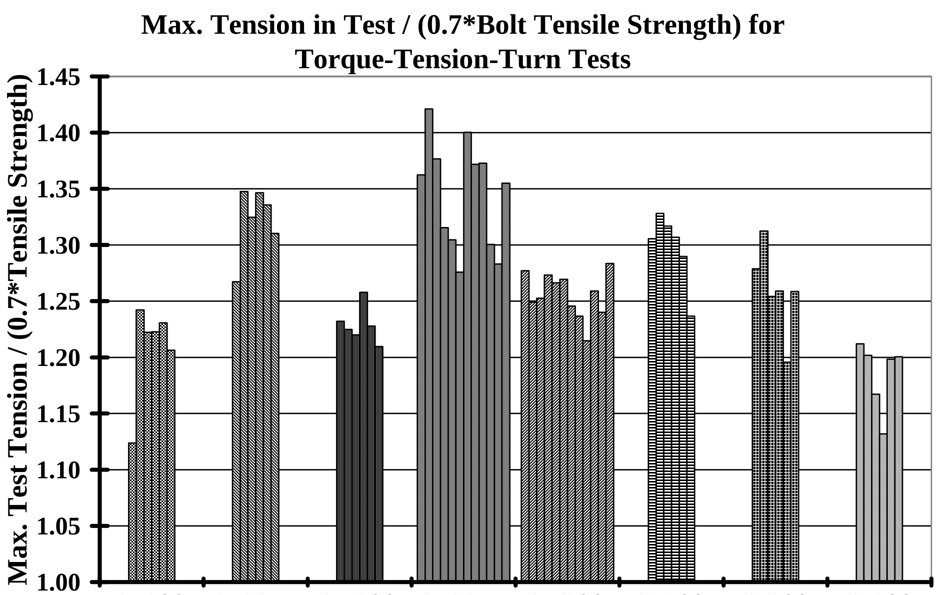


*Figure 4.27 Maximum Tension in Test / (0.7*Bolt Tensile Strength) for Torque-Tension-Turn Tests*

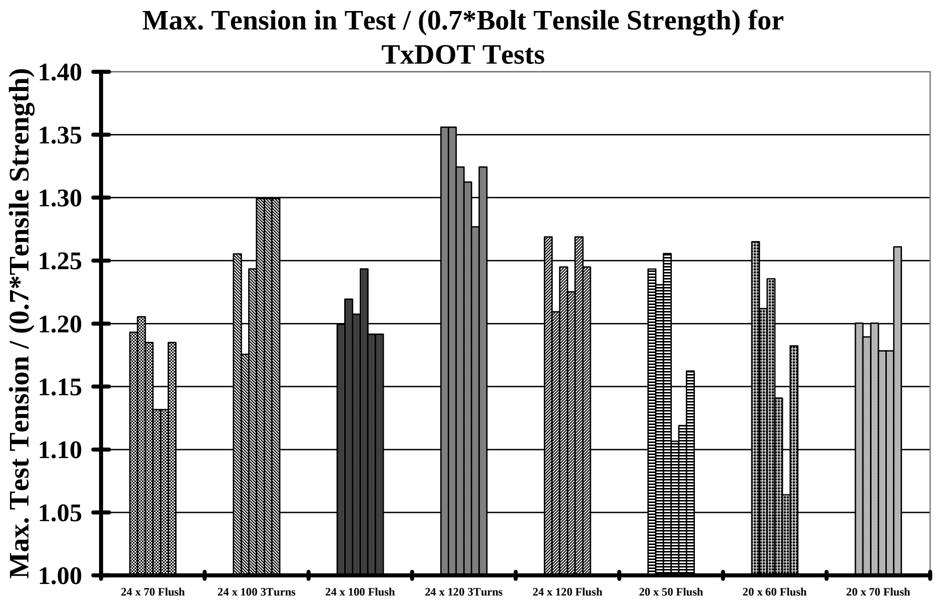


*Figure 4.28 Maximum Tension in Test / (0.7*Bolt Tensile Strength) for TxDOT Tests*

### 4.8.2 Ductility

An additional tenet of the rotational capacity test requires that the minimum tension in the fastener must be equal to or greater than 1.15 times the minimum required installation tension at a rotation equal to 2 times the minimum required nut rotation. The testing conditions and equipment used in the TxDOT tests are nearly the same as the conditions for a field rotational capacity test with a bolt calibrator. As a result, the TxDOT test results were used to analyze the behavior of the bolts with respect to the ductility requirements of the rotational capacity test. The use of a bolt calibrator to monitor fastener tension allows the person performing the test to control the snug tension. To take into account the control over the snug tension, the turns in the TxDOT tests were measured from the 10% of minimum specified tensile strength snug condition. Figure 4.29 shows the relationship between the tension at 1 turn with the minimum required installation tension for the TxDOT tests. All values are significantly greater that 1.15. Therefore, the bolts have satisfactory tensions at this point on the tension-turn curve. However, some of the bolts in the solid plate tests were found to have ultimate rotational capacities close to 1 turn (Figure 4.23), which is only twice the specified turn-of-the-nut rotation for 24 mm bolts with lengths greater than 4 times the diameter. The ultimate rotational capacities for bolts tested in the TxDOT Skidmore test setups are shown in Figure 4.30. The 24 mm x 100 mm 3 turn bolts had rotational capacities as low as 1.167 and the lowest rotational capacity for the 24 mm x 120 mm 3 turns bolts was 1.333 turns. For a 1/2 turn installation requirement, these bolts do not have much ductility beyond 2 times the required nut rotation, or 1 turn.

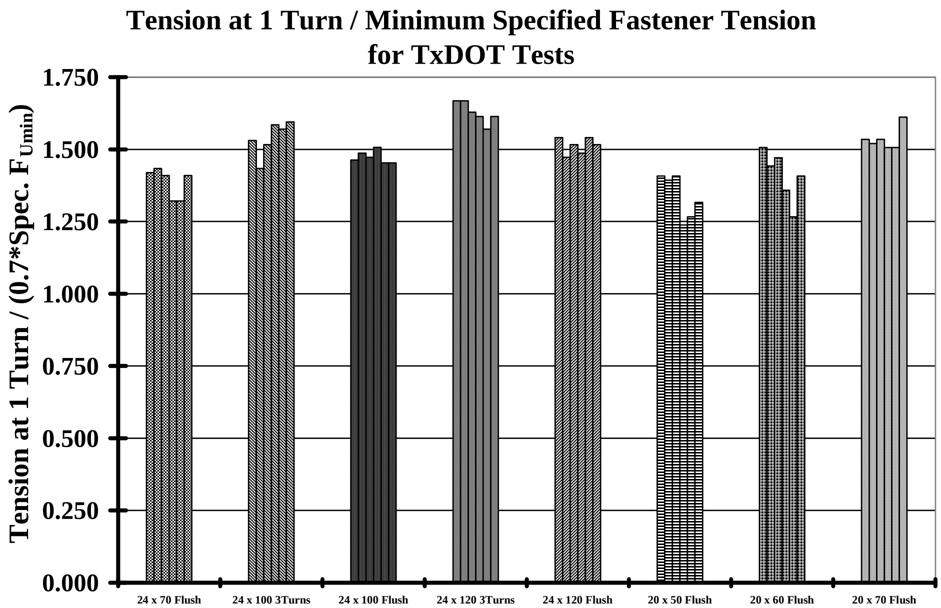


*Figure 4.29 Tension at 1 Turn / Minimum Specified Fastener Tension for TxDOT Tests*

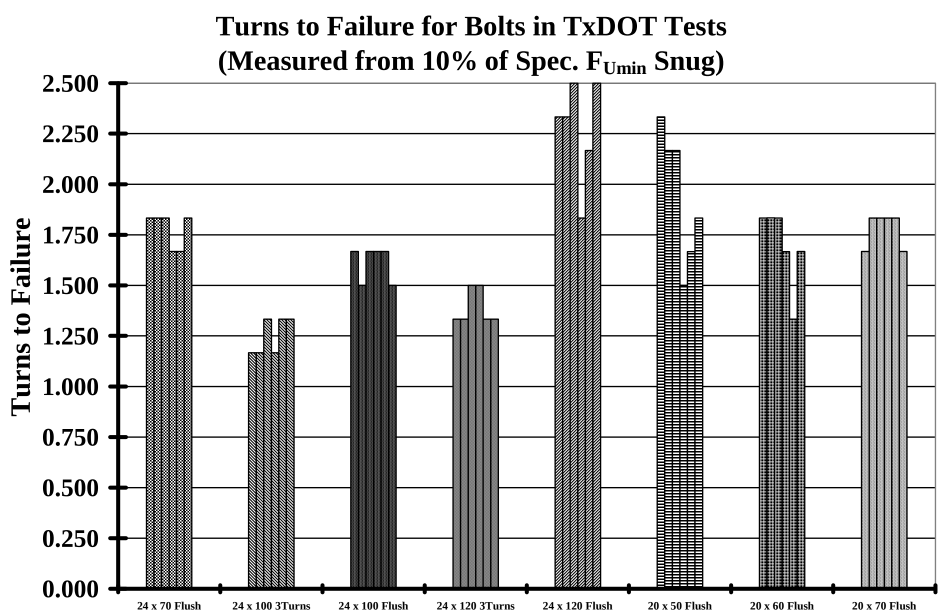


*Figure 4.30 Turns to Failure for All Bolts in TxDOT Tests*

### 4.8.2 Rotation Verification Test

In the field, a rotation verification test must be performed in a bolt calibrator to ensure that the specified number of turn tightens the fastener to the proper tension. The rotation verification test requires that the specified turns of the nut produce a fastener tension in the calibrator that is no less than 5 % higher than the minimum specifies fastener tension. The required nut rotations to reach 1.05 x 0.7 x minimum specified tensile strength for those tests that most resembled real field installation conditions, the TxDOT tests, are presented in Figure 4.31.

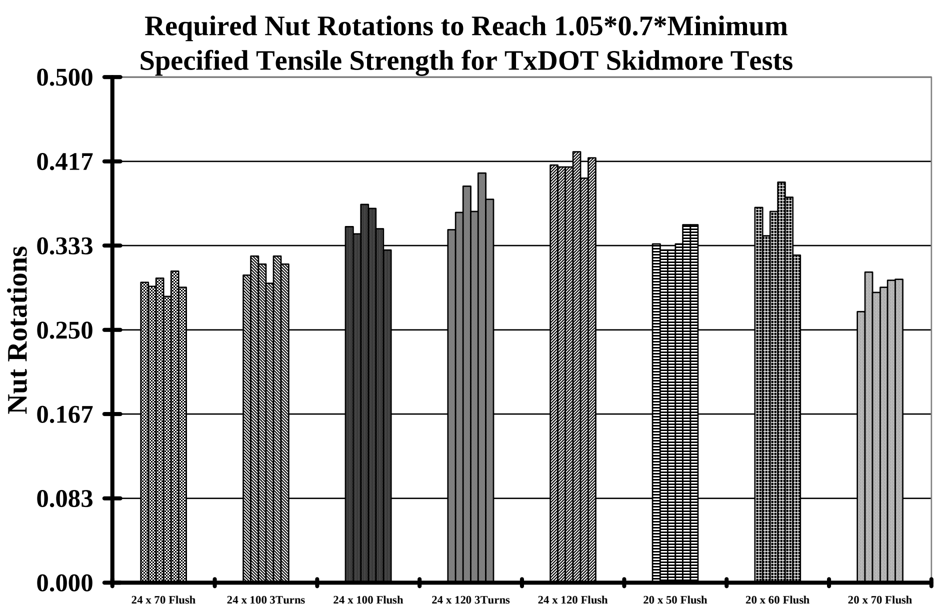


***Figure 4.31 Required Nut Rotations to Reach 1.05*0.70*Minimum Specified Tensile Strength in TxDOT Tests***

# CHAPTER 4

# DATA PRESENTATION

## 4.1 INTRODUCTION

The results of the torque-tension-turn tests and the tension-turn tests were analyzed with respect to the current installation requirements of the AASHTO turn-of-the-nut procedure and rotational capacity test. Two different snug conditions and the output from test setups of differing stiffness were analyzed and utilized to best determine the installation requirements for the A325M metric bolts. Alternate installation requirements are presented when the current AASHTO requirements for inch bolts were not satisfactory for the A325M metric bolts. Final recommendations for changes to the current bolt specification are given in Chapter 5.

## 4.2 SNUG CONDITION

The AASHTO Specification states the a snug tight condition “may be attained by a few impacts of an impact wrench or the full effort of a man using an ordinary spud wrench”. This definition leaves no quantifiable value of snug in terms of fastener tension or torque. A man using an impact wrench could conceivably apply a much larger torque than a man using a spud wrench. The snug definition becomes more ambiguous when considering the variance of “full effort" from one man to another. However, the snug condition is very important to the effectiveness of the turn-of-the-nut method. The specified nut rotations to reach the required tension in the fastener are applied after the bolt has been tightened to a snug condition.

The previous research on inch bolts used a snug tension equal to 10% of the minimum specified tensile strength of the fastener to determine the nut rotation requirements [11]. For the A325M metric bolt research project, two snug tension conditions were examined: 10% of the minimum specified tensile strength (20.3 kN for the 20 mm bolts and 29.3 kN for the 24 mm bolts) and a fastener tension of 44.48 kN (10 kips). Figures 4.1 and 4.2 show the torque required to reach these snug tension conditions for each bolt tested in a torque-tension-turn test. These plots include data from different test setups ranging from load cell - solid plate to short grip Skidmore. As expected, the test setup did not influence the torque-tension relationship The data also includes bolts tested in the as received and weathered conditions. The removal of lubrication did not have any appreciable effect on the torque-tension relationship. The torque required for the 20 mm bolts was less than the torque required for the 24 mm bolts for both snug conditions.

The maximum torque a man can apply using an ordinary spud wrench was estimated to be 203 N-m (150 ft-lb). The torques required to produce the 10% of minimum specified tensile strength snug condition are representative of this 150 ft-lb maximum torque input. The maximum and minimum torques were 273 N-m (201 ft-lb) and 107 N-m (79 ft-lb), respectively.

The torques required to reach the 44.48 kN snug tension condition were significantly higher than the torques required to reach 10% of the minimum specified tensile strength. The 44.48 kN snug torques ranged from 210 N-m (155 ft-lb) and 343 N-m (253 ft-lb). All of these torques are above the estimated maximum torque input of 203 N-m (150 ft-lb). The 44.48 kN snug condition requires torques that are not plausible for a man with a spud wrench. However, this snug condition can be used to estimate the maximum snug when using an impact wrench.

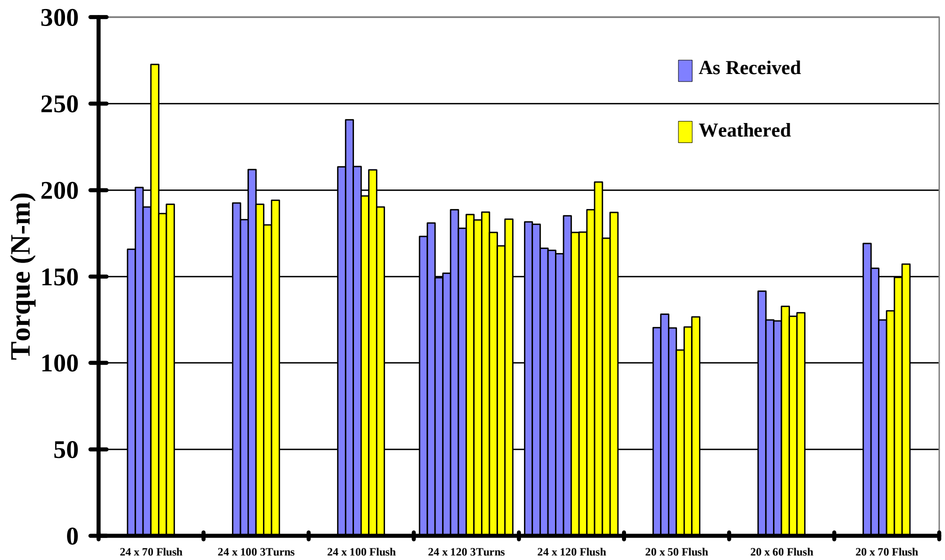


***Figure 4.1 Torque Required to Reach 10% of Minimum Specified Tensile Strength***

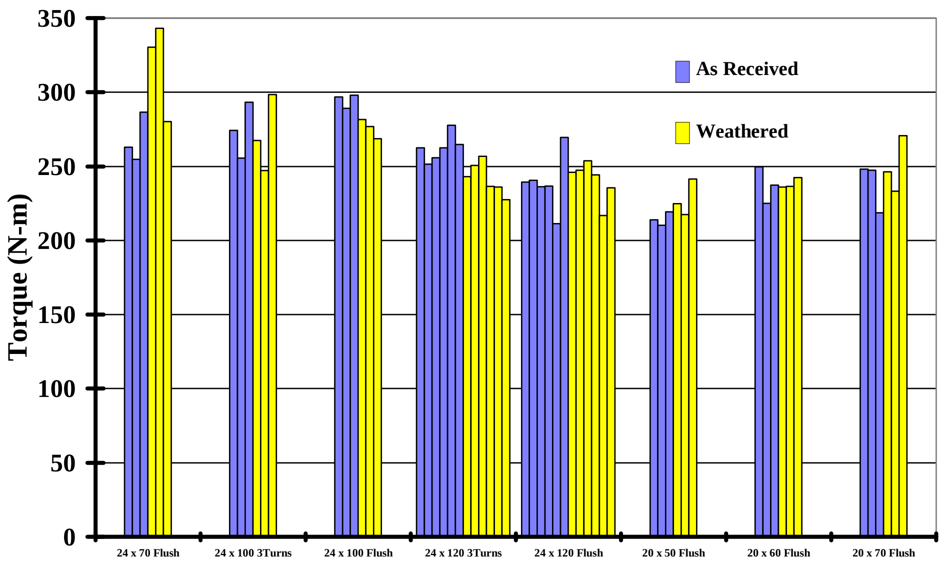


***Figure 4.2  Torque Required to Reach 44.48 kN Tension in Fastener***

In addition, the 44.48 snug tension is more likely to be on the linear-elastic portion of the tension-turn curve. Figure 4.3 shows a graph of the initial part of a tension-turn load curve up to the minimum specified fastener tension for a 20 mm x 70 mm lubricated flush grip bolt in the load cell box test setup. The graph clearly shows that the 44.48 kN snug point lies on the linear elastic portion of the loading curve. The 20.3 kN snug point occurs before the curve becomes linear. Figure 4.4 indicates similar results for the same type of bolt tested in a solid plate. In this case, the 20.3 kN point is closer to the start of the linear portion of the tension-turn curve. These results are typical for all bolts tested in the torque-tension-turn and solid plate tests. The 44.48 kN snug tension condition provides a more uniform starting point for examining the relative behavior of bolts in the various test setups because the point is on the linear-elastic portion of the curve.

Using a snug point that occurs before the curve becomes linear would make determination of the influence of the test setups on bolt behavior difficult. The amount of "play" or initial looseness in the test setup and the bolt-nut-washer-assembly at the start of loading varies from test to test and setup to setup. As a result, the length of the curve before the linear portion is different for each bolt tested.

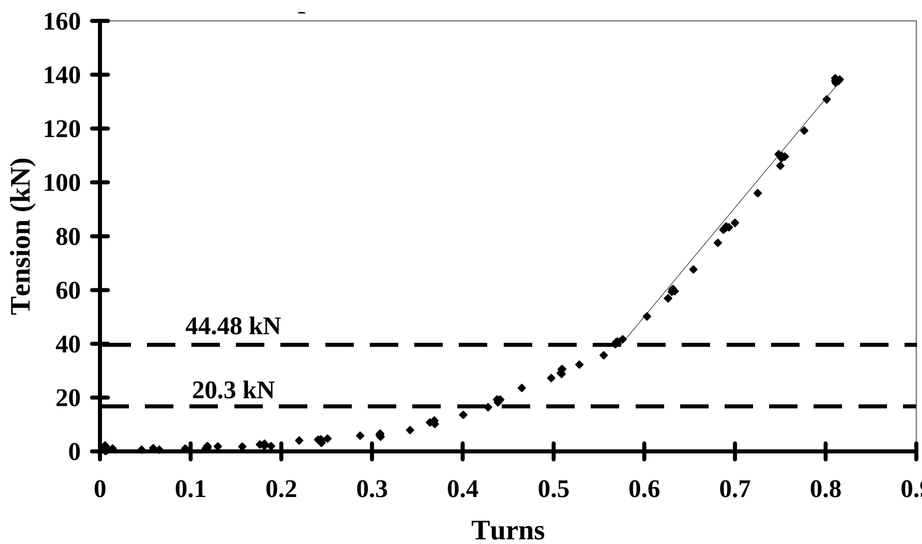


***Figure 4.3 Initial Tension-Turn Curve for a 20 x 70 Flush Grip Bolt up to Minimum Specified Fastener Tension in Load Cell Box***

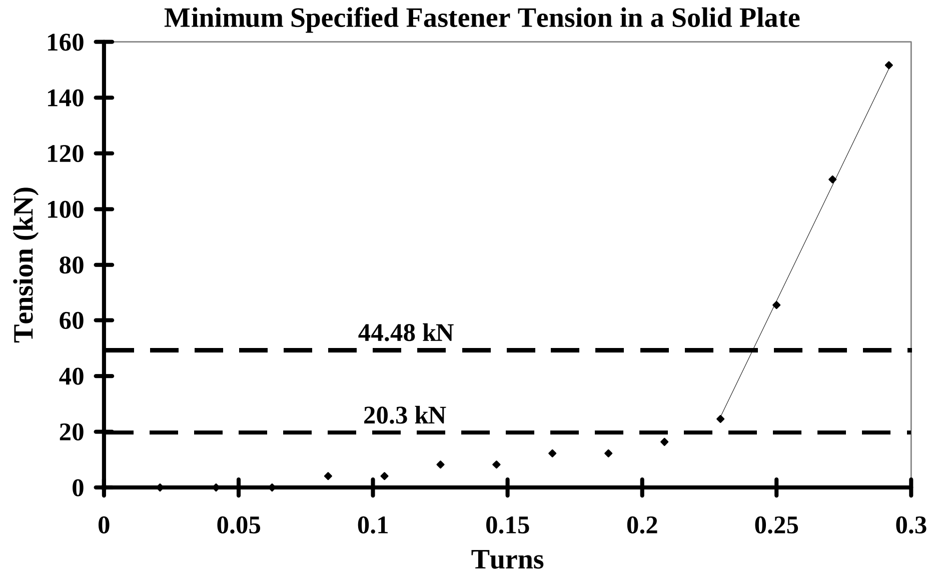


***Figure 4.4 Initial Tension-Turn Curve for a 20 x 70 Flush Grip Bolt up to Minimum Specified Fastener Tension in a Solid Plate***

In this research, the ultimate rotational capacity of each bolt was measured from the 44.48 kN snug. This tension represents the estimated maximum snug condition in the field. Conversely, the nut rotations required to reach the minimum specified fastener tension were measured from the 10% of minimum specified tensile strength snug condition. This condition represents the estimated minimum snug condition in the field. The 44.48 kN snug condition was also used to compare the initial stiffness of each bolt in the different test setups.

### 4.3 EFFECT OF WEATHERING UPON LUBRICATION PERFORMANCE

The results of all testing indicated no significant difference in bolt behavior between those bolts that were tested in the as received condition and those that were weathered in the laboratory before testing. Table 4.1 compares the average nut factors for the as received and weathered bolts tested in the torque-tension-turn tests. The nut factors indicate that the installation torques for each of the lubrication conditions were remarkably similar from the snug point (as presented in Figures 4.1 and 4.2) up to and including the maximum torque in the

***Table 4.1  Average Nut Factors for Torque-Tension-Turn Tests***

| **Diameter** | **Length** | **Grip** | **Average Nut Factor** | |
|---|---|---|---|---|
| **(mm)** | **(mm)** | | **As Received** | **Weathered** |
| 24 | 70 | Flush | 0.225 | 0.208 |
| | 100 | 3 Turns | 0.212 | 0.200 |
| | 100 | Flush | 0.211 | 0.211 |
| | 120 | 3 Turns | 0.206 | 0.203 |
| | 120 | Flush | 0.206 | 0.207 |
| 20 | 50 | Flush | 0.200 | 0.228 |
| | 60 | Flush | 0.241 | 0.251 |
| | 70 | Flush | 0.224 | 0.240 |

test. In addition, there was no significant difference in ductility as measured by turns to failure. Table 4.2 compares the average turns to failure in the torque-tension-turn tests for each lubrication condition. The turns to failure were measured from a snug tension equal to 44.48 kN. The results indicate that the lubricant supplied on the as received fastener was not significantly degraded by the simulated weathering done in the laboratory.

***Table 4.2 Average Turns to Failure for Torque-Tension-Turn Tests***

| Diameter | Length | Grip | Test Setup | Average Turns to Failure | |
|---|---|---|---|---|---|
| (mm) | (mm) | | | As Received | Weathered |
| 24 | 70 | Flush | Load Cell Box | 1.80 | 1.92 |
| | 100 | 3 Turns | Load Cell Box | 1.26 | 1.28 |
| | 100 | Flush | Load Cell Box | 1.69 | 1.62 |
| | 120 | 3 Turns | Load Cell Box | 1.33 | 1.38 |
| | 120 | 3 Turns | L. C.- Solid Plate | 1.42 | 1.38 |
| | 120 | Flush | Load Cell Box | 2.20 | 2.22 |
| | 120 | Flush | L. C.- Solid Plate | 2.22 | 2.12 |
| 20 | 50 | Flush | Short Grip Skidmore | 2.19 | 2.06 |
| | 60 | Flush | Short Grip Skidmore | 1.82 | 1.76 |
| | 70 | Flush | Load Cell Box | 1.76 | 1.78 |

## 4.4 BOLT PERFORMANCE IN DIFFERENT TEST SETUPS

Figures 4.5 through 4.9 graphically contrast the performance of bolts tested in the solid plate setup with the results of replicate tests in other test setups. The plots display the effects of the wide spectrum of test setup stiffnesses upon the rotational performance of the bolts. In each case, the bolt tested in the solid plate had the highest initial stiffness and the lowest ductility, or ultimate rotational capacity. The bolts tested in the TxDOT Skidmore test setups had the lowest initial stiffness, with the exception of the 24 mm x 70 mm and the 20 mm x 50 mm bolts. These bolts had essentially had essentially the same stiffness in the load cell box and the TxDOT Skidmore test setups.

The stiffness of a multiple ply connection is expected to fall between the hydraulic bolt calibrator and solid plate extremes. The results from the test setup with the lowest stiffness were used to establish nut rotation requirements because a bolt tested in this setup requires the highest number of turns to reach a specified tension. Similarly, the data from the solid plate test setup was used to check ultimate rotational capacity limitations because the reduced rotational ductility of a bolt tested in this setup results in the lowest number of turns to failure.

The inelastic portion of the tension-turn curve was found to be independent of the test setup. The 24 x 120 flush grip bolt tension-turn curves in Figure 4.7 illustrate the fact that the nut rotations in the inelastic range of the solid plate and TxDOT tests are approximately equal (1.54 turns and 1.56 turns), despite large differences in initial stiffness. The inelastic behavior of the bolt is not a function of the type of test setup.

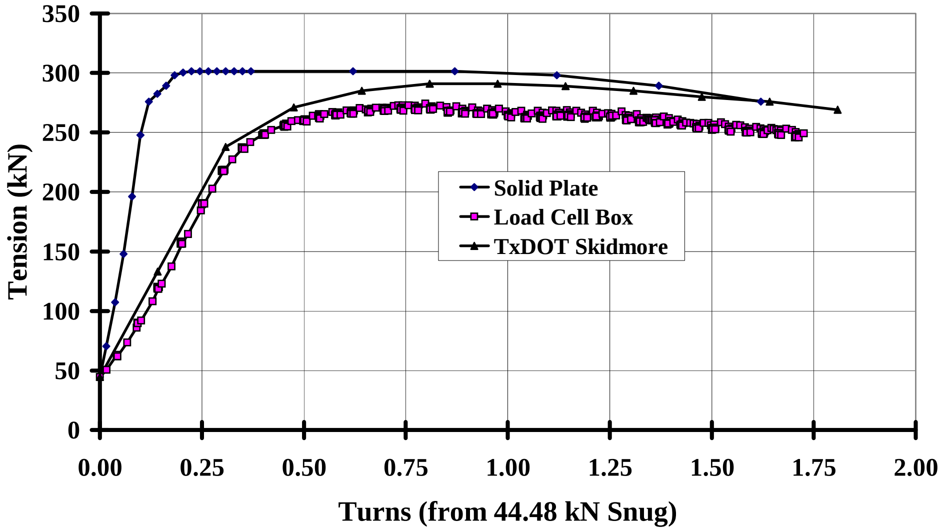


*Figure 4.5 Relative Performance of 24 x 70 Flush Grip Bolts in Different Test Setups*

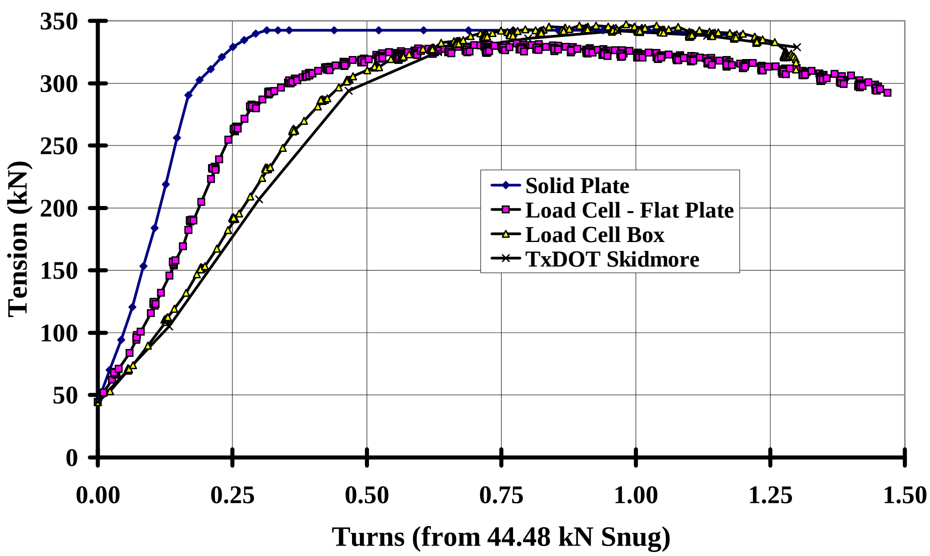


*Figure 4.6 Relative Performance of 24 x 120 3 Turn Grip Bolts in Different Test Setups*

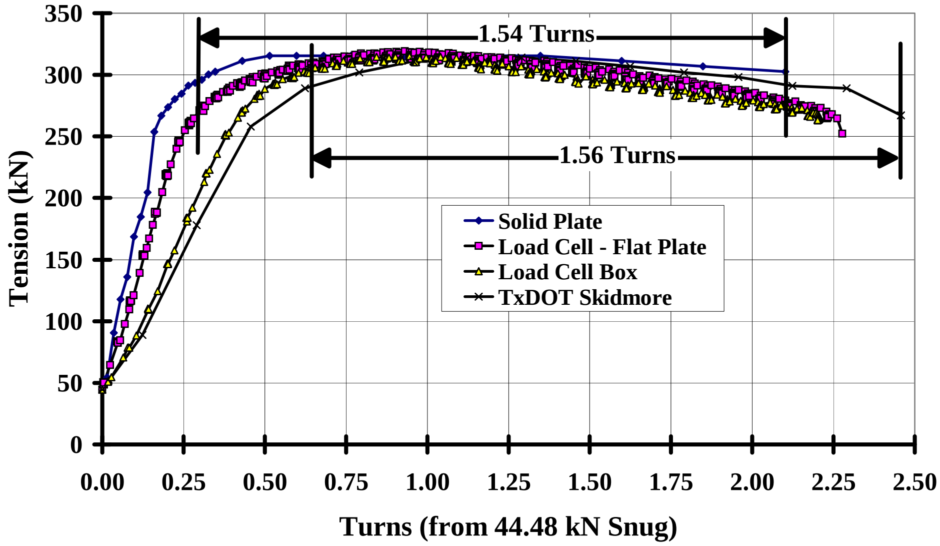


***Figure 4.7 Relative Performance of 24 x 120 Flush Grip Bolts in Different Test Setups***

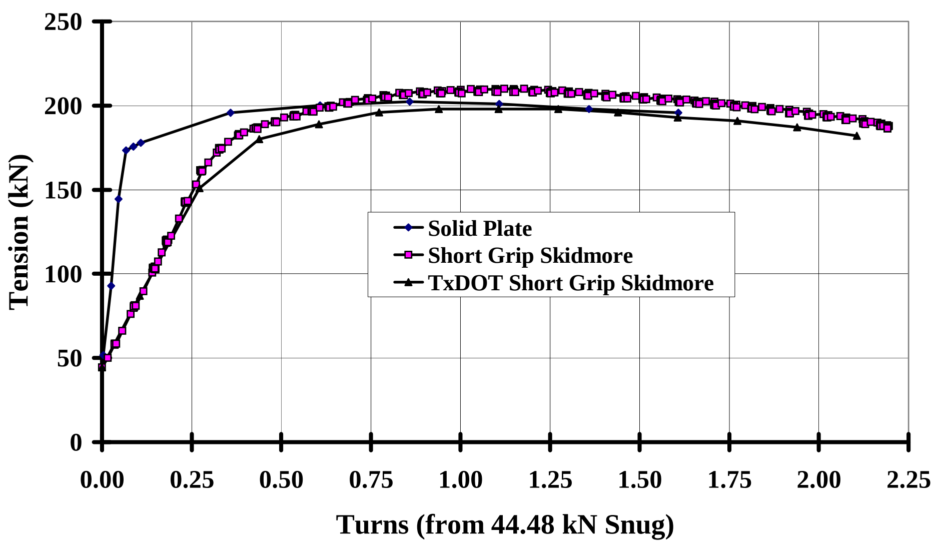


***Figure 4.8 Relative Performance of 20 x 50 Flush Grip Bolts in Different Test Setups***

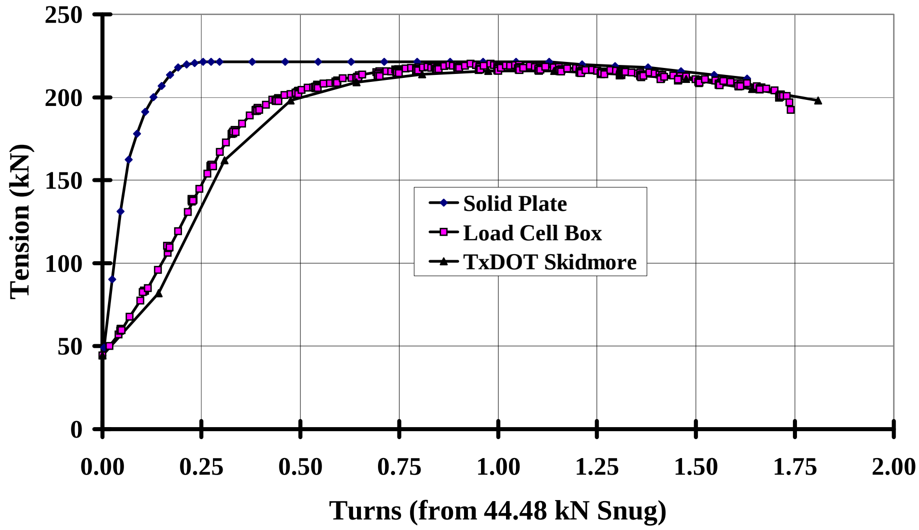


***Figure 4.9 Relative Performance of 20 x 70 Flush Grip Bolts in Different Test Setups***

### 4.5 ROTATIONAL STIFFNESS

The relationship between tension and nut rotations from a snug tension of 44.48 kN to the minimum specified fastener tension for a given bolt is reasonably linear. Therefore, the "rotational stiffness" of any bolt can be calculated by using linear regression to determine the slope of the tension-turn curve between these points. The slope of the linear portion of the tension-turn curve is defined by the following equation,

$$\text{Rotational Stiffness} = \Delta T / \Delta N \qquad (4.1)$$

where $\Delta T$ is the change in fastener tension and $\Delta N$ is the change in nut rotation, as depicted in Figure 4.10.

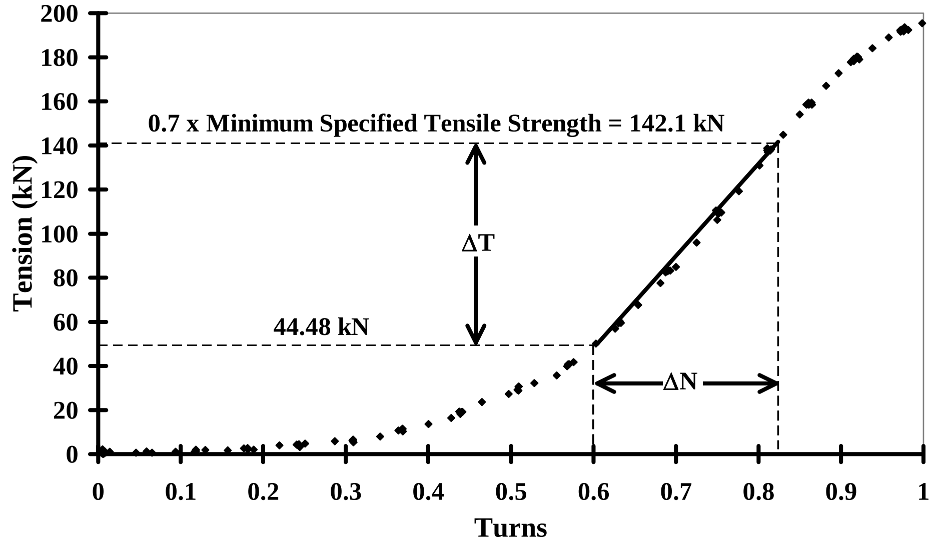


***Figure 4.10 Example of Rotational Stiffness Calculation for 20 x 70 Flush Grip Bolt in Load Cell Box Test Setup***

The rotational stiffnesses for bolts tested in the torque-tension-turn tests are compared with the solid plate test results in Figures 4.11 and 4.13. For the 50 mm and 70 mm bolts (both 20 mm and 24 mm diameters), the rotational stiffnesses were 4 to 5 times higher in the solid plate than in the short grip Skidmore and load cell box tests. For the 24 mm x 120 mm bolts tested in the solid plates, the rotational stiffnesses were approximately 2.2 times larger than the stiffnesses from the load cell box test setup, and 1.5 time times larger than stiffnesses from the load cell - flat plate test setup. As expected, the graphs also indicate an increase in rotational stiffness for shorter grip lengths in the solid plate tests.

Figures 4.12 and 4.14 show the influence of grip length on rotational stiffness in the torque-tension-turn tests. As with the solid plate results, the load cell - solid plate, load cell box, and short grip Skidmore test results indicate an inverse relationship between rotational stiffness and grip length. It should be noted that the TxDOT Skidmore results are not included because the linear portions of these curves do not contain enough points to accurately define a slope.

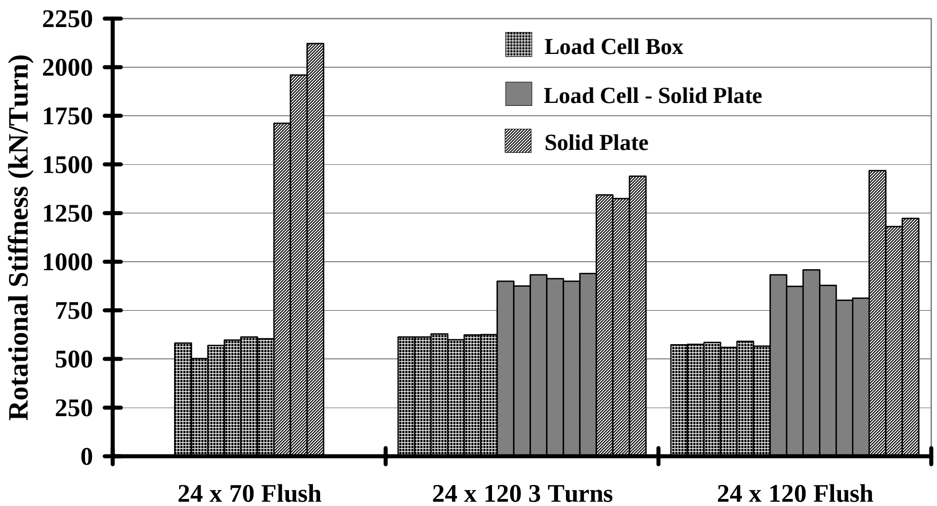


***Figure 4.11 Comparison of Rotational Stiffnesses for 24 mm Bolts in Torque-Tension-Turn and Solid Plate Tests***

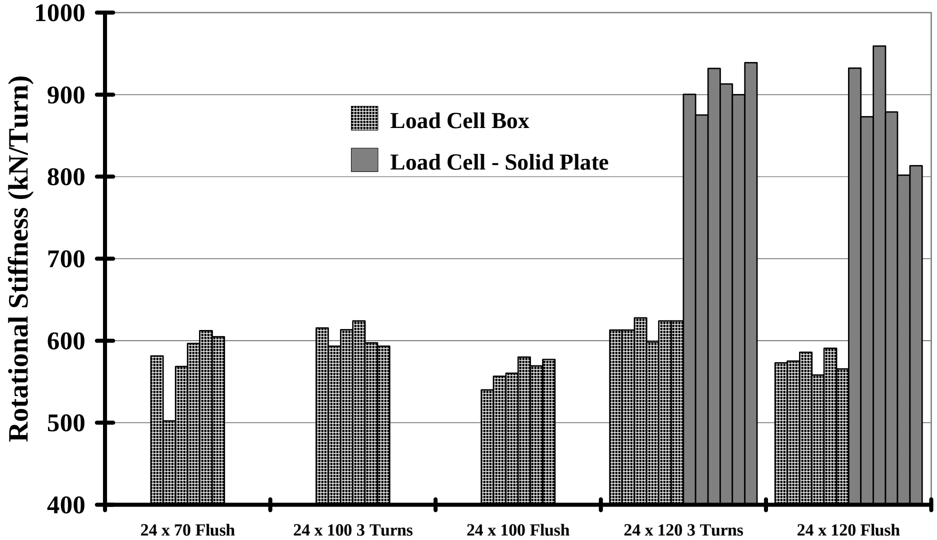


***Figure 4.12 Comparison of Rotational Stiffnesses for 24 mm Bolts in Load Cell - Solid Plate and Load Cell Box Tests***

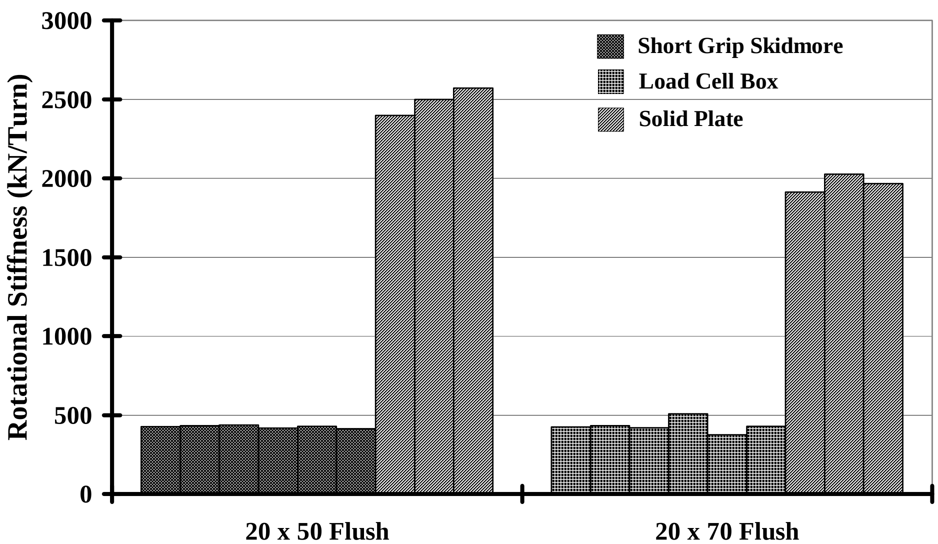


***Figure 4.13 Comparison of Rotational Stiffnesses for 20 mm Bolts in Torque-Tension-Turn and Solid Plate Tests***

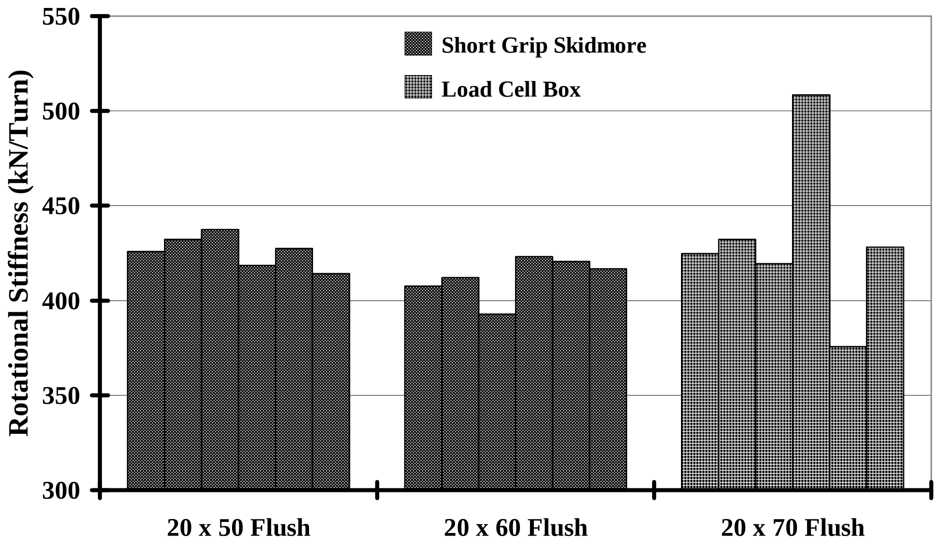


***Figure 4.14 Comparison of Rotational Stiffnesses for 20 mm Bolts in Torque-Tension-Turn Tests***

## 4.6 NUT ROTATION

The number of nut rotations required to reach the minimum specified fastener tension from a snug tension equal to 10% of the minimum specified tensile strength was calculated for every bolt tested. The snug tension was equal to 20.3 kN for the 20 mm bolts and 29.3 kN for the 24 mm bolts. As stated previously, the bolts tested in the lower stiffness test setups required the highest number of nut rotations. The nut rotation requirements for the load cell - flat plate, load cell box, short grip Skidmore, and TxDOT Skidmore tests are presented in Figures 4.15 through 4.22. In each graph, the nut rotation axis has $30^{o}$ degree gridline increments.

The 24 mm x 120 mm 3 turn and flush grip results (Figures 4.18 and 4.19) indicate that the required number of turns to reach the minimum specified fastener tension decreases as the stiffness of the test setup increases, as expected. The influence of test setup on the required nut rotations is minimal for the other results because the overall stiffnesses of the load cell box and Skidmore test setups examined in these cases are about the same.

A comparison of the required nut rotations for the two grip conditions for the 24 mm x 100 mm bolts (Figures 4.16 and 4.17) and the 24 mm x 120 mm bolts (Figures 4.18 and 4.19) shows that the 3 turns bolts required slightly less turns than the flush bolts. An examination of the required nut rotations for the 20 mm bolts (Figures 4.20 through 4.21) also indicates an increase in the required turns for longer grip lengths in the same test setup.

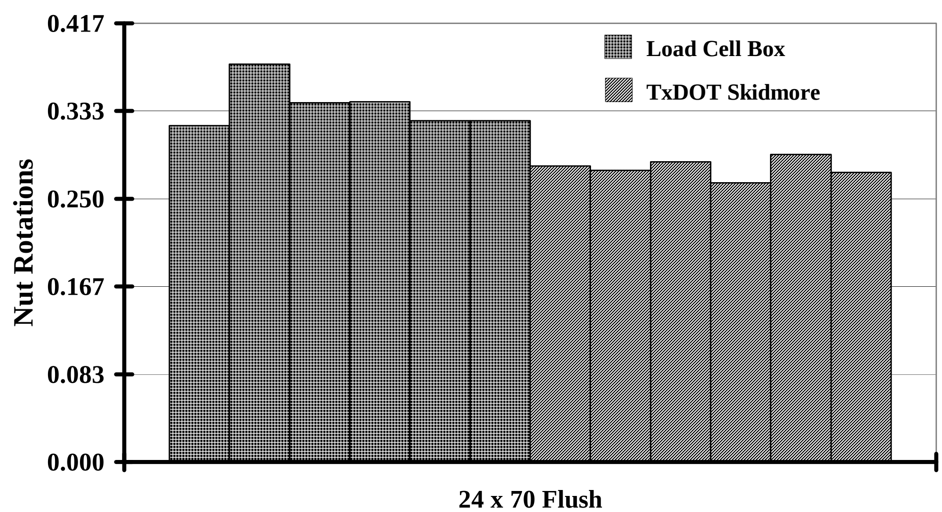


***Figure 4.15 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 70 Flush Grip Bolts***

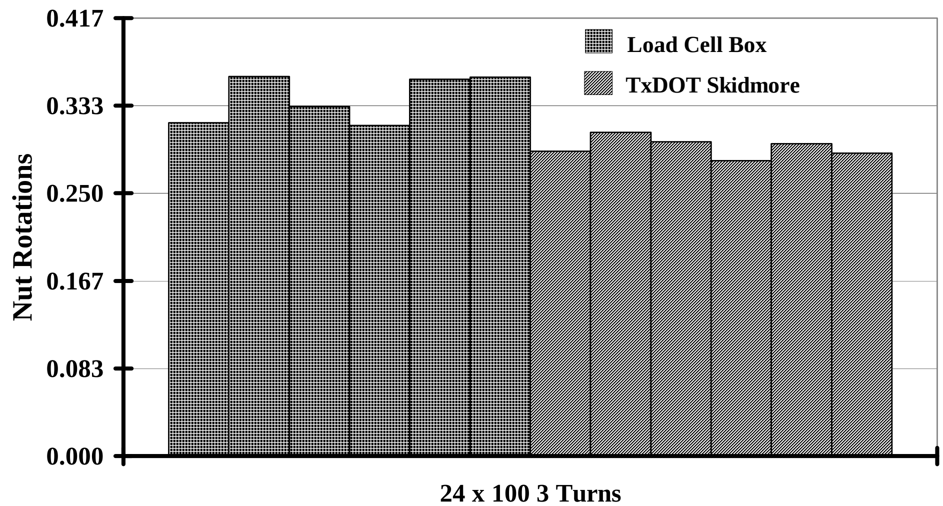


***Figure 4.16 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 100 3 Turn Grip Bolts***

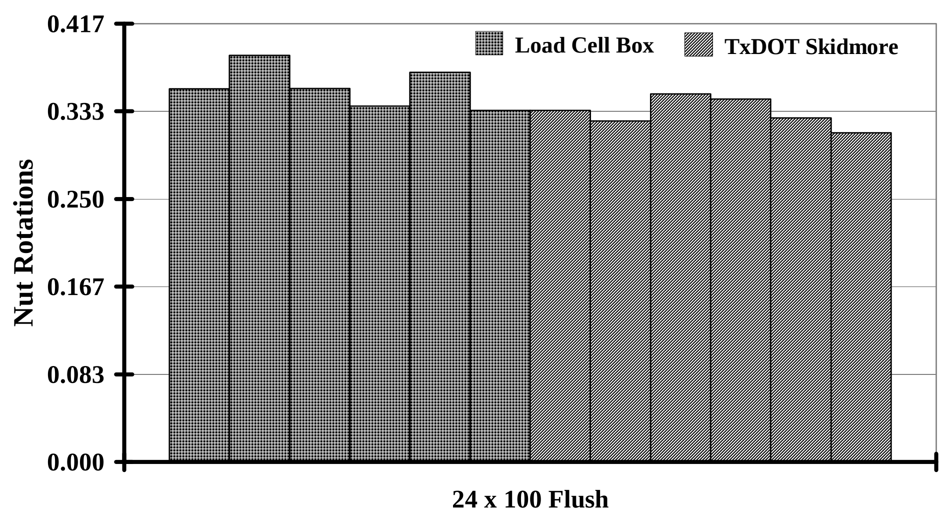


***Figure 4.17 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 100 Flush Grip Bolts***

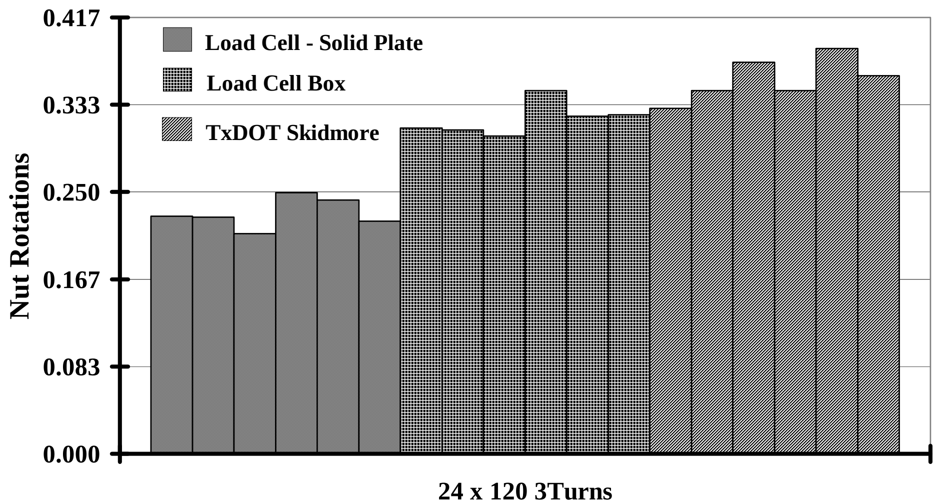


***Figure 4.18 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 120 3 Turn Grip Bolts***

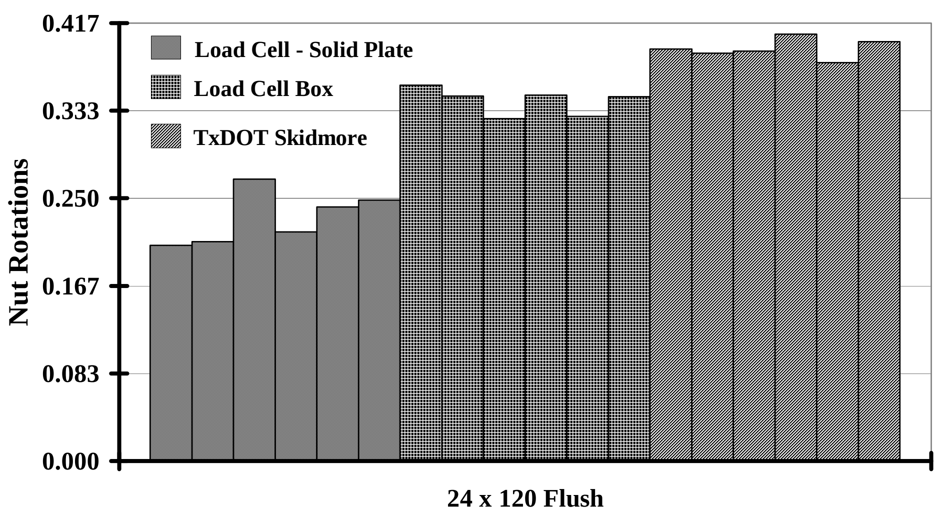


***Figure 4.19 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 24 x 120 Flush Grip Bolts***

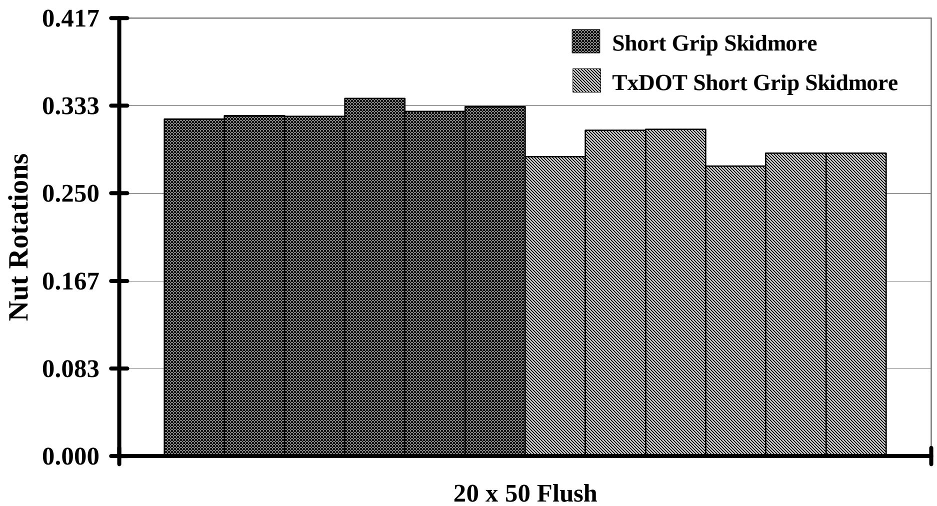


*Figure 4.20  Required Nut Rotations to Reach Minimum Specified Fastener Tension for 20 x 50 Flush Grip Bolts*

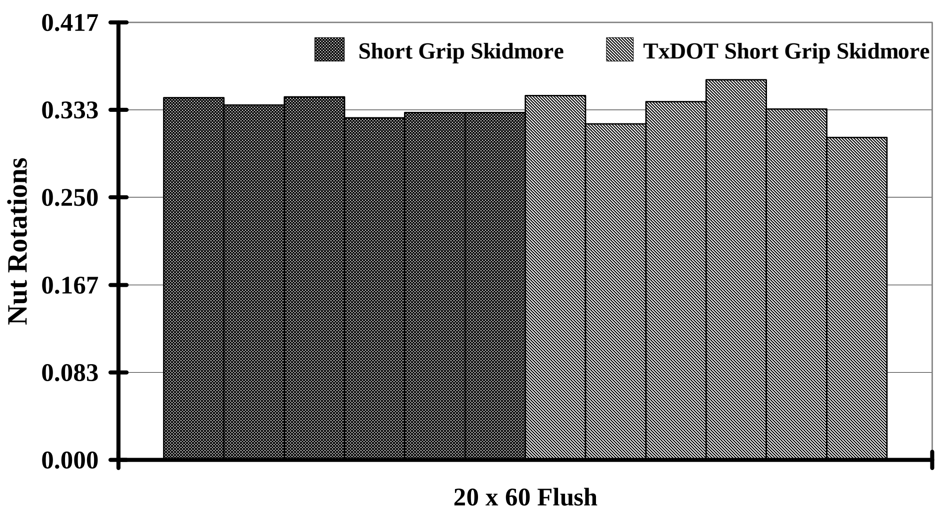


*Figure 4.21  Required Nut Rotations to Reach Minimum Specified Fastener Tension for 20 x 60 Flush Grip Bolts*

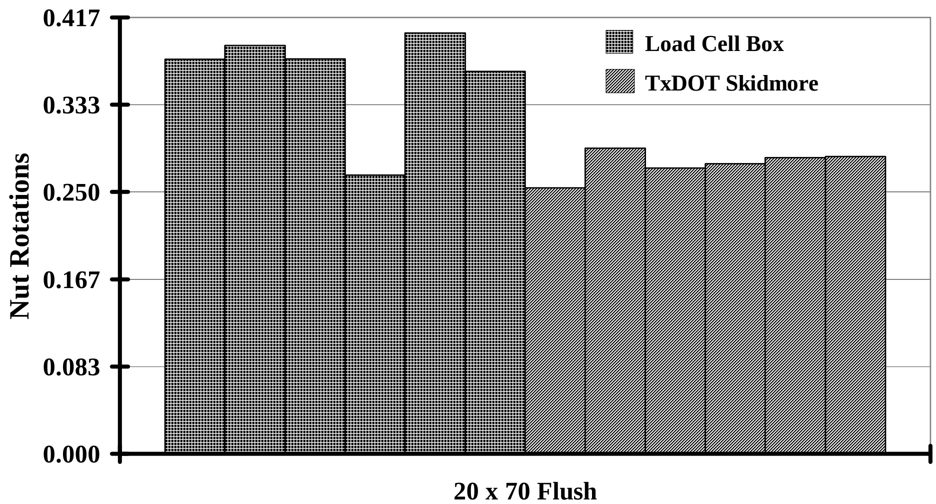


***Figure 4.22 Required Nut Rotations to Reach Minimum Specified Fastener Tension for 20 x 70 Flush Grip Bolts***

## 4.7 ULTIMATE NUT ROTATIONAL CAPACITY

The ultimate nut rotational capacity was determined in the stiffest test setup, the solid plate, which provides the least bolt ductility, or lowest number of turns to failure. The values of rotational capacity in the solid plate test were determined using a 44.48 kN snug condition. The number of turns to failure for each set of bolts tested in the solid plate setup are plotted in Figure 4.23. The lowest rotational capacity recorded was 1.074 for one of the 20 mm x 70 mm 3 turn grip bolts. This value is nearly 2/3 turn less than the rotational capacities for the same bolt with a flush grip condition. The differences in rotational capacity shown in Figure 4.23 clearly indicate that reducing the grip length can significantly reduce ductility.

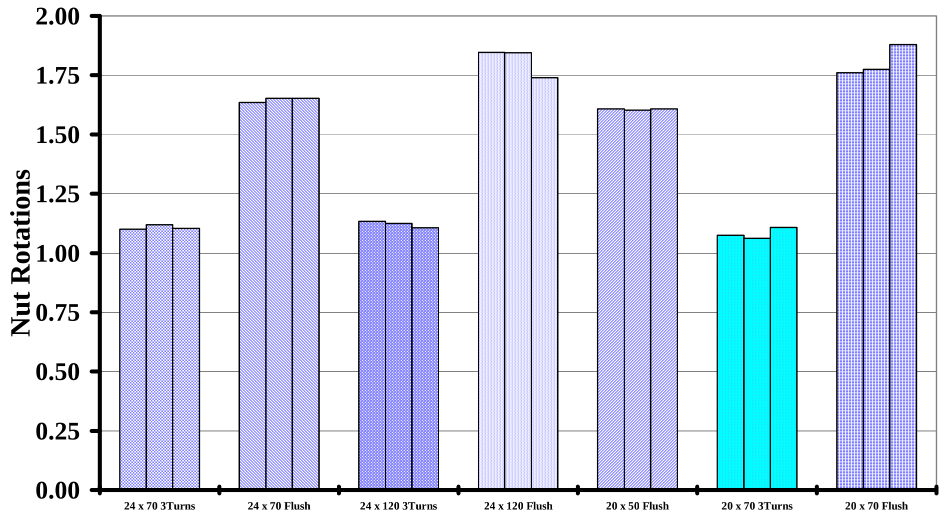


***Figure 4.23 Ultimate Rotational Capacity of Bolts in Solid Plate Test***

## 4.8 ROTATIONAL CAPACITY TEST REQUIREMENTS

### 4.8.1 Nut Factor / Maximum Torque

The relationship between torque and tension in the torque-tension-turn tests was found be linear, as shown in Figure 4.24. To analyze the performance of each bolt with respect to the rotational capacity test, the average nut factor was calculated each torque-tension-turn bolt test. The rotational capacity test does not allow for a nut factor greater than 0.25 at any point in the test for long bolts. Only 4 bolts, or 6.7% of the test matrix would fail to pass this test in the field. Figure 4.24 shows the average nut factors for all the torque-tension-turn tests. The average nut factor was equal to 0.21

For short bolts, where no tension readings are possible, the maximum allowable torque in the rotational capacity test is defined by the following equation,

$$\text{Max. Torque} = 0.25 \times 1.15 \times 0.70 \times \text{spec. } F_{Umin} \times \text{Dia.} \qquad (5)$$

This equation assumes that the maximum fastener tension is only 15% greater than the minimum specified fastener tension. The maximum torque exceeded the maximum allowable torque in 75% of the torque-tension-turn tests, as shown in Figure 4.26. In order to show the severity of the 15% assumption, the maximum tension in each of the torque-tension turn and TxDOT tests was divided by 70% of the actual tensile strength, which is significantly greater than the specified minimum tensile strength. These results are presented in Figures 4.27 and 4.28. The assumed 15% increase in fastener tension is very conservative. The majority of the bolts showed increases greater than 20%.

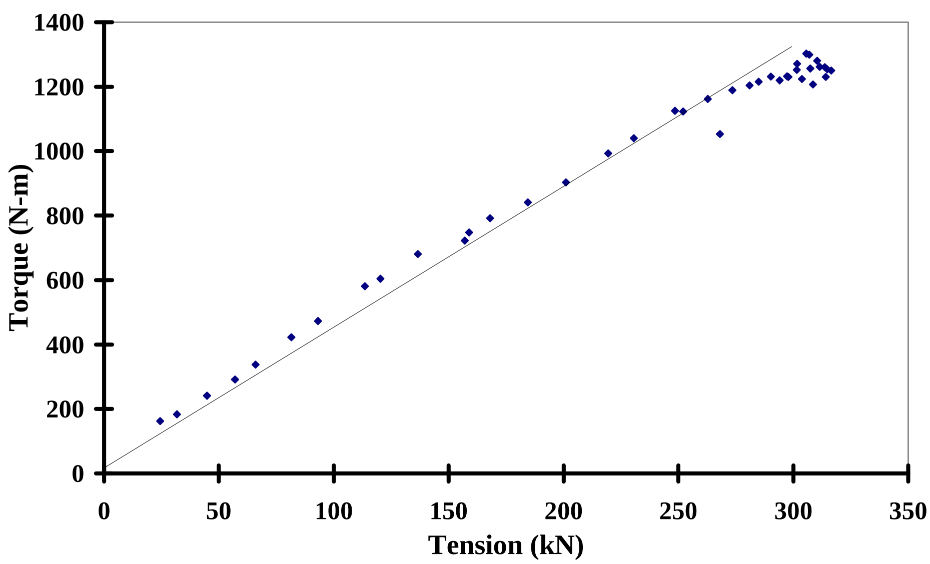


***Figure 4.24 Torque vs. Tension for 24 x 120 Flush Grip Bolt in Load Cell Box Test Setup***

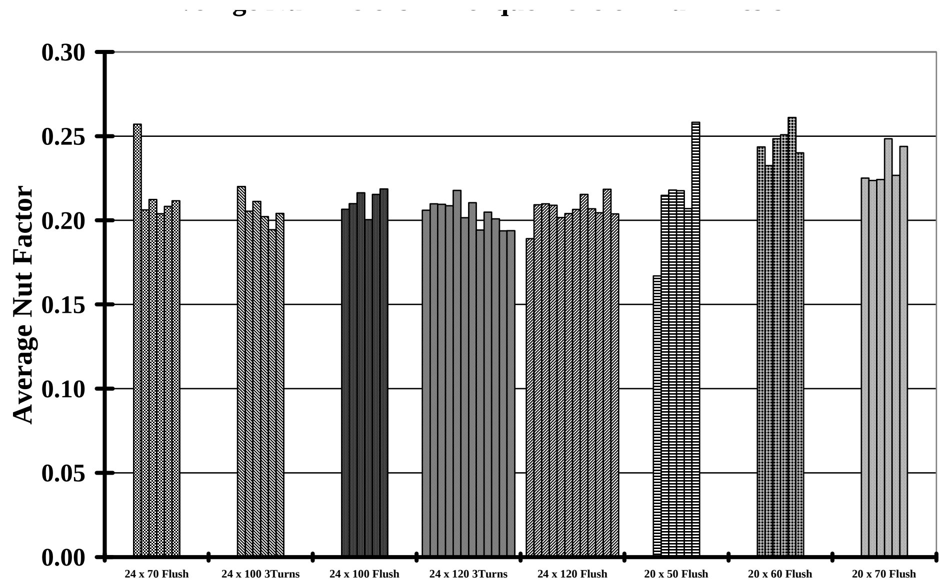


*Figure 4.25  Average Nut Factors in Torque-Tension-Turn Tests*

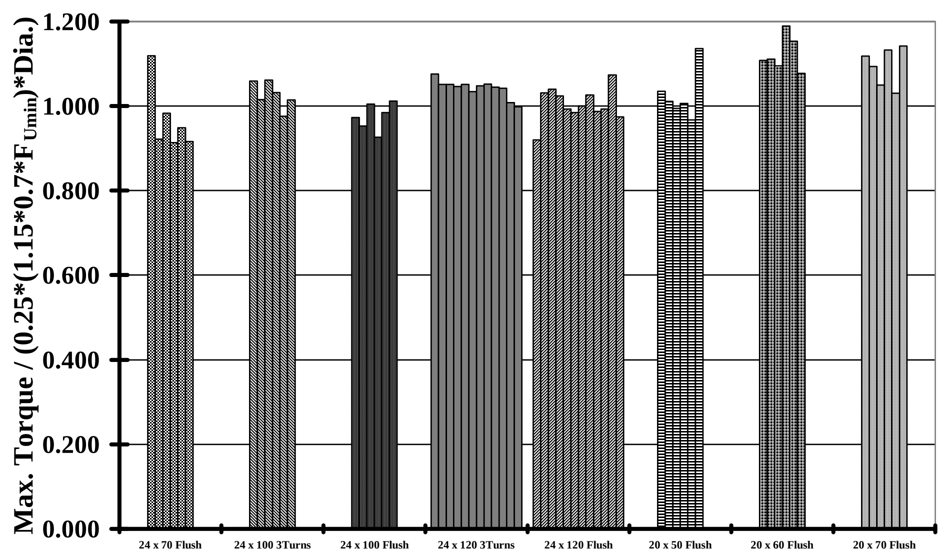


*Figure 4.26  Maximum Torque in Test / AASHTO Maximum Allowable Torque*

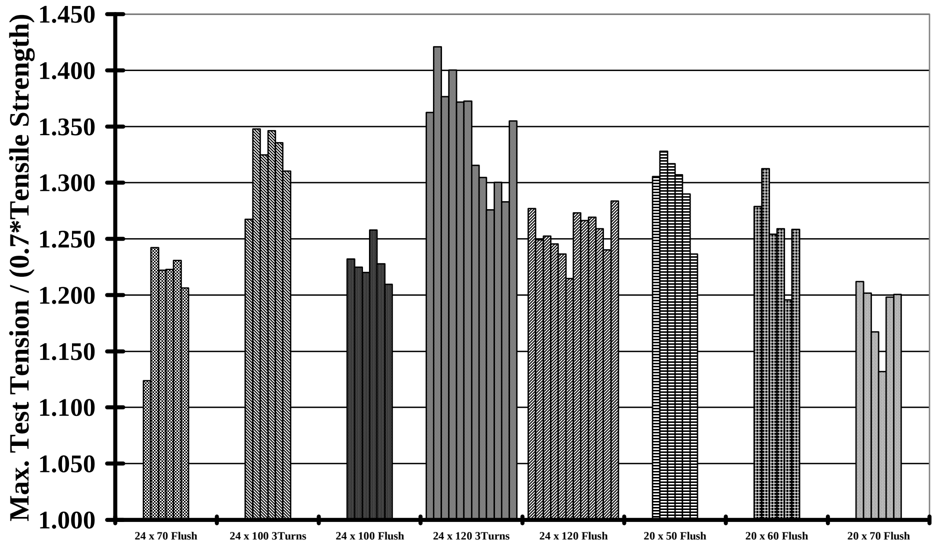


***Figure 4.27 Maximum Tension in Test / (0.7*Bolt Tensile Strength) for Torque-Tension-Turn Tests***

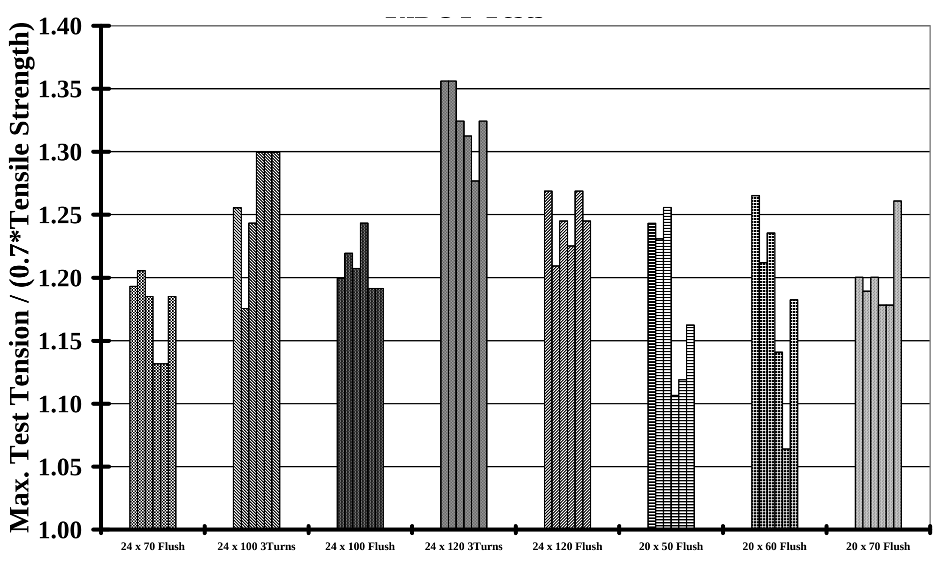


***Figure 4.28 Maximum Tension in Test / (0.7*Bolt Tensile Strength) for TxDOT Tests***

### 4.8.2 Ductility

An additional tenet of the rotational capacity test requires that the minimum tension in the fastener must be equal to or greater than 1.15 times the minimum required installation tension at a rotation equal to 2 times the minimum required nut rotation. The testing conditions and equipment used in the TxDOT tests are nearly the same as the conditions for a field rotational capacity test with a bolt calibrator. As a result, the TxDOT test results were used to analyze the behavior of the bolts with respect to the ductility requirements of the rotational capacity test. The use of a bolt calibrator to monitor fastener tension allows the person performing the test to control the snug tension. To take into account the control over the snug tension, the turns in the TxDOT tests were measured from the 10% of minimum specified tensile strength snug condition. Figure 4.29 shows the relationship between the tension at 1 turn with the minimum required installation tension for the TxDOT tests. All values are significantly greater that 1.15. Therefore, the bolts have satisfactory tensions at this point on the tension-turn curve. However, some of the bolts in the solid plate tests were found to have ultimate rotational capacities close to 1 turn (Figure 4.23), which is only twice the specified turn-of-the-nut rotation for 24 mm bolts with lengths greater than 4 times the diameter. The ultimate rotational capacities for bolts tested in the TxDOT Skidmore test setups are shown in Figure 4.30. The 24 mm x 100 mm 3 turn bolts had rotational capacities as low as 1.167 and the lowest rotational capacity for the 24 mm x 120 mm 3 turns bolts was 1.333 turns. For a 1/2 turn installation requirement, these bolts do not have much ductility beyond 2 times the required nut rotation, or 1 turn.

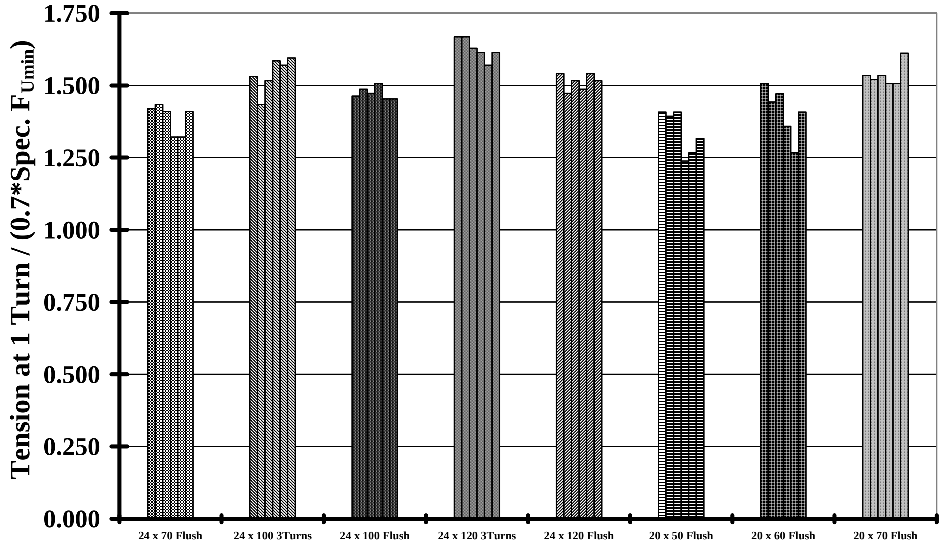


***Figure 4.29 Tension at 1 Turn / Minimum Specified Fastener Tension for TxDOT Tests***

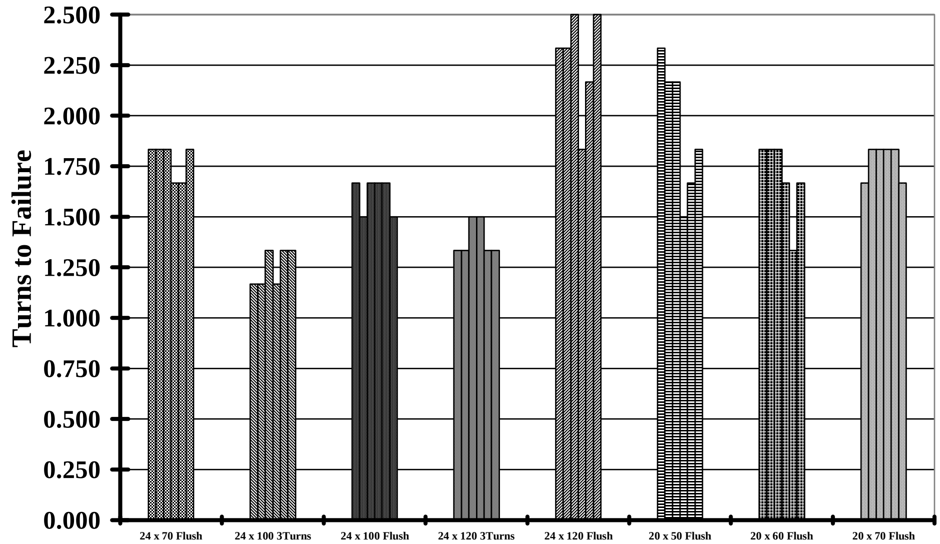


***Figure 4.30 Turns to Failure for All Bolts in TxDOT Tests***

### 4.8.2 Rotation Verification Test

In the field, a rotation verification test must be performed in a bolt calibrator to ensure that the specified number of turn tightens the fastener to the proper tension. The rotation verification test requires that the specified turns of the nut produce a fastener tension in the calibrator that is no less than 5 % higher than the minimum specifies fastener tension. The required nut rotations to reach 1.05 x 0.7 x minimum specified tensile strength for those tests that most resembled real field installation conditions, the TxDOT tests, are presented in Figure 4.31.

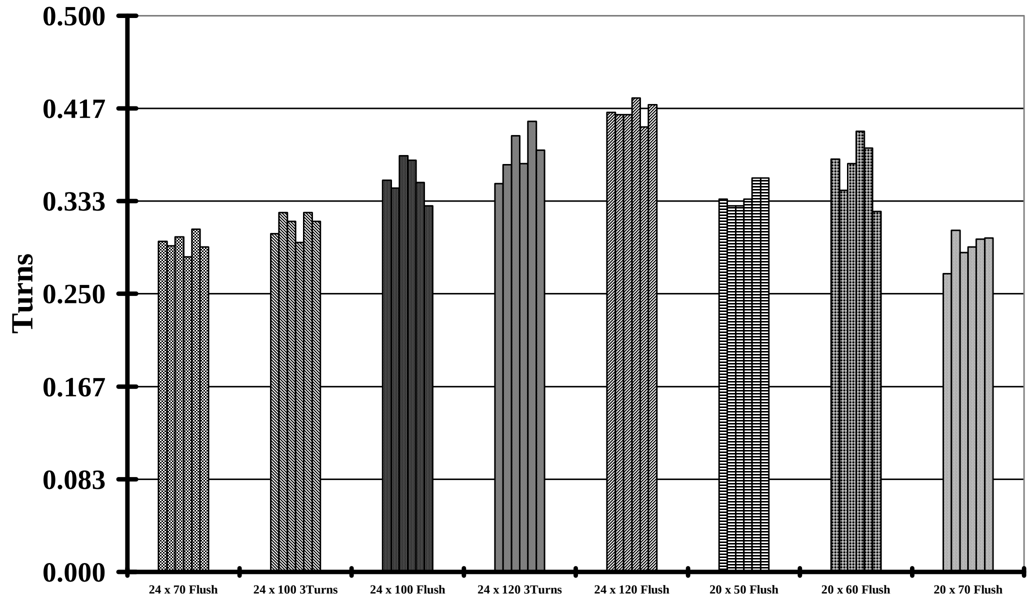


***Figure 4.31 Required Nut Rotations to Reach 1.05*0.70*Minimum Specified Tensile Strength in TxDOT Skidmore Tests***

***Table 4.3 Tension-Turn Test Results for 20 mm x 50 mm Flush Grip Bolt Tightened with an Impact Wrench in a Solid Plate***

| Bolt | Snug Tension | 1/2 Turn Tension | 1 Turn Tension | 1 Turn+30$^{o}$ Tension | $N_{ULT}$ |
|---|---|---|---|---|---|
| 1 | 29.0 | 195.7 | 194.4 | 193.9 | 1.51 |
| 2 | 34.8 | 193.5 | 200.2 | 199.3 | 1.65 |
| 3 | 46.4 | 204.6 | 197.5 | 196.6 | 1.59 |

# CHAPTER 5

# RECOMMENDED SPECIFICATION CHANGES

## 5.1 INTRODUCTION

The results of the A325M metric bolt tests are compared with the AASHTO specifications for the turn-of-the-nut procedure and rotational capacity test. The results indicate a need to set new installation requirements for the turn-of-the-nut procedure. These recommended changes to the specification are examined with respect to the rotational capacity test and the rotational verification test. A summary of the conclusions and recommended specification alterations is listed in Chapter 6.

## 5.2 TURN-OF-THE-NUT REQUIREMENTS

The general tension-turn behavior for the metric bolts tested in this research project is depicted in Figure 5.1. The minimum required fastener tension is significantly below the inelastic plateau. The maximum fastener tensions were more than 25% greater than the minimum specified fastener tension (Figures 4.28 and 4.29). The AASHTO Specification assumes only a 15% increase in tension, based on the results presented in the Bolt Guide and in the commentary of the Bolt Specification. The difference in maximum fastener tension is amplified by comparing the turns to reach the minimum required fastener tension with the turns to reach 0.7 x measured bolt tensile strength, as shown in Figure 5.2. The turns required to reach the minimum fastener tension are not large enough to fully yield the bolt, as expected with the turn-of-the-nut procedure. Because the minimum fastener tension is on the linear-elastic portion of the tension-turn curve, the force in the bolt is very sensitive to small changes in nut rotation. The ideal turn-of-the-nut would result in a bolt elongation that correlates with the inelastic part of the curve, where bolt tension is not sensitive to small variances in nut rotation. In this ideal case, the turn-of-the-nut requirement would induce a bolt tension that far exceeds the minimum required tension with typical bolts, which have a tensile strength above the specified minimum.

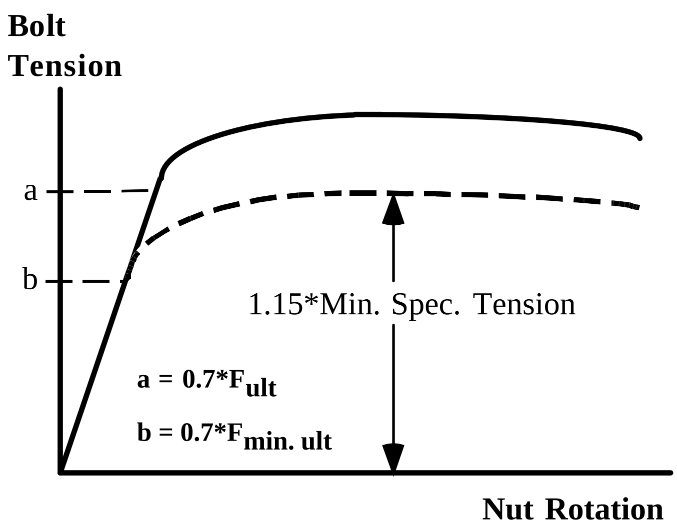


***Figure 5.1 General Tension-Turn Behavior***

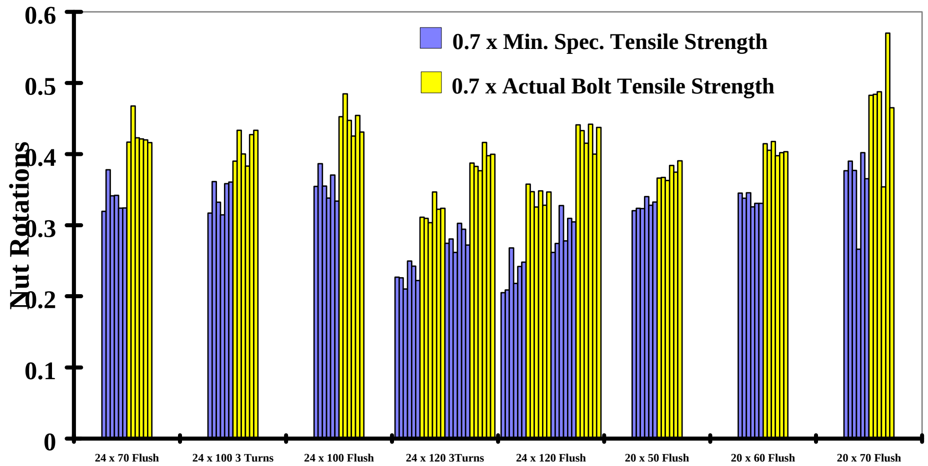


***Figure 5.2 Comparison of Turns Required to Reach 0.7 x Min. Spec. Tensile Strength with Turns Required to Reach 0.7 x Actual Bolt Tensile Strength in Torque-Tension-Turn Tests***

Figure 5.3 shows the range of turns required to reach the minimum specified fastener tension from the least stiff test setup for each length to diameter ratio examined. All turns were measured from a snug tension equal to 10% of the minimum specified tensile strength for each bolt diameter (20.3 kN for the 20 mm bolts and 29.3 kN for the 24 mm bolts). The turn values are indicated with the square symbols and the range is given by the horizontal lines. The current AASHTO turn-of-the-nut requirements (using the $30^{o}$ tolerance) are indicated with a dotted line. The complete nut rotation results were presented in Figures 4.15 through 4.22. For bolts with a length to diameter ratio equal to or less than 4, AASHTO specifies 1/3 turn to reach the required tension. For bolts with a

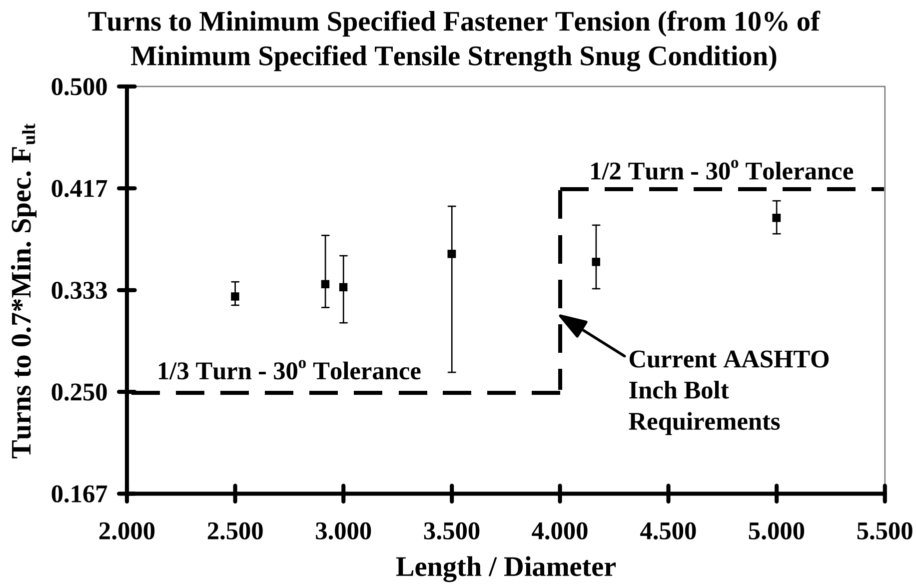


***Figure 5.3 Comparison of Turns to Minimum Specified Fastener Tension with Current AASHTO Turn-of-the-Nut Requirements***

length to diameter ratio greater than 4, AASHTO specifies 1/2 turn to reach the required tension. These AASHTO turn-of-the-nut requirements have positive and negative tolerances of $30^o$. The metric bolt results indicate that 1/3 turn will not induce the required tension in all of the bolts with length to diameter ratios less than 4. If the tolerance of $30^o$ is used, none of the shorter bolts would reach the required fastener tension. The bolts with length to diameters ratios greater than 4 reach the minimum specified tension in less turns than the 1/2 turn minus $30^o$ tolerance requirement. However, these results indicate that bolts with higher length to diameter ratios (but still less than the next AASHTO turn-of-the-nut plateau with length to diameter ratios greater than 8) may require more turns than the negative tolerance allows.

New AASHTO turn-of-the-nut requirements for A325M bolts should be set to reflect the tension-turn behavior of these bolts. The specified turns for bolts with length to diameter ratios less than or equal to 4 should be changed from 1/3 turn to 1/2 turn.

## 5.3 ROTATIONAL CAPACITY TEST

### 5.3.1 Nut Factor / Maximum Torque

The nut factors calculated for the torque-tension-turn tests (as presented in Figure 4.24) indicate that the maximum allowable nut factor of 0.25 in the rotational capacity test is applicable to metric bolts. Using a maximum nut factor of 0.25 would result in a an acceptance rate greater than 93% for the tested A325M metric bolts.

For short bolts, where no tension readings are possible, the maximum allowable torque in the rotational capacity test is equal to 0.25 x maximum fastener tension x diameter. The maximum fastener tension is assumed to be 15% greater than the minimum specified fastener tension. The minimum specified bolt tensile strength is used instead of the measured bolt tensile strength The maximum test torque results presented in Figure 4.26 demonstrate the severity of the tensile strength assumption. 75% of the metric bolts tests had torque values greater than the maximum allowable value. Figures 4.27 and 4.28 show that the assumed 15% difference in fastener tension is more representative of the increase in fastener tension from 0.7 x measured bolt tensile strength than the increase in fastener tension from 0.7 x minimum specified bolt tensile strength. Therefore, the assumed maximum fastener tension in a short bolt rotational capacity test should be calculated as 1.15 x 0.7 x average bolt tensile strength from mill reports.

### 5.3.2 Ductility

The rotational capacity test requires that the minimum tension in the fastener must be equal to or greater than 1.15 times the minimum required installation tension at a rotation equal to 2 times the AASHTO turn-of-the-nut requirement. For all length to diameter ratios tested in this research, a 1/2 turn nut rotation requirement is recommended. Therefore, at 1 turn, the bolt tension must be 15% greater than the minimum fastener tension.

The test conditions and equipment used in the TxDOT Skidmore tests best model a field rotational capacity test. The turns to failure in Figures 4.23 and 4.30 show that the metric bolts have sufficient ductility to reach 1 turn from snug in both the solid plate and TxDOT Skidmore test setups. In addition, the ratios of fastener tension at 1 turn to the minimum specified fastener tension (Figure 4.29) indicate that all of the metric bolts had tensions greater than 1.15 x minimum specified fastener tension at a nut rotation equal to twice the recommended turn-of-the-nut requirement.

## 5.4 ROTATION VERIFICATION TEST

The rotation verification test must be performed in a bolt calibrator to ensure that the specified turns of the nut induce the required tension in the fastener. This test requires that the specified number of turns produce a fastener tension in the bolt calibrator that is no less than 5% greater than the minimum specified fastener tension. If 1/2 turn with $30^o$ tolerances is specified for all of the length to diameter ratios tested, the nut rotation results in Figure 4.31 show that some of the 24 mm x 120 mm flush grip bolts in the TxDOT tests do not satisfy this requirement. However, if the negative tolerance is eliminated, all the bolts pass the rotation verification test. Therefore, the negative tolerances for turns should be eliminated.

# CHAPTER 6

# SUMMARY OF CONCLUSIONS AND RECOMMENDED CHANGES TO THE AASHTO SPECIFICATION

## 6.1 CONCLUSIONS

The results of 70 torque-tension-turn tests and 79 tension-turn tests on 20 mm and 24 mm diameter A325M metric bolts with two different lubrication and grip conditons in 5 test setups lead to the following conclusions and recommended changes to the AASHTO Bolt Specification.

- The lubricant supplied on the as received fastener was not significantly degraded by the simulated weathering done in the laboratory.
- The inelastic portion of the tension-turn curve was found to be independent of the test setup. The nut rotations in the elastic range for different types of test setup are approximately equal.
- The required turns to reach a specific tension decrease as the stiffness of the test setup increases.
- The ductility of a bolt decreases as the stiffness of test setup increases.
- The grip length is inversely proportional to the rotational stiffness and directly proportional to the required nut rotations to reach a specified fastener tension.
- The ductiliy of a bolt is significantly decreased by reducing the grip length.

- The minimum required fastener tension for overstrength bolts is significantly below the plateau of plastic behavior. The turns required to reach the minimum fastener tension are not large enough to fully yield the bolt, as expected with the AASHTO Turn-of-the-Nut procedure.
- The AASHTO Turn-of-the-Nut requirement of 1/3 turn for bolts with length to diameters ratios less than 4 is not sufficient to reach the minimum specified fastener tension.
- The assumed 15% increase in fastener tension from the minimum specified tension to the maximum tension in the AASHTO Rotational Capacity Test for short bolts is extremely conservative. As a result, a large number of the bolt tests had torques that exceeded the maximum allowable torque for short bolts.
- Some of the A325M bolts would not pass the rotation verification test if the $30^o$ turn tolerances are taken into account. All bolts would pass the rotation verification test if the negative 30o tolerances are eliminated.

## 6.2 RECOMMENDED CHANGES TO THE AASHTO BOLT SPECIFICATION

- The specified turn-of-the-nut requirement for bolts with length to diameter ratios less than or equal to 4 should be changed from 1/3 turn to 1/2 turn.
- The negative $30^o$ tolerance for turns should be eliminated for all length to diameter ratios.

- The assumed maximum fastener tension in a short bolt rotational capacity test should be calculated as 1.15*0.7*average bolt tensile strength from mill reports.

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