COMPARISON OF STRUCTURAL BOLTING ASSEMBLIES INSTALLED BY THE TURN-OF-NUT AND DIRECT-TENSION-INDICATOR METHODS AND THEIR RESPECTIVE RESERVE DUCTILITY

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1.0 Introduction

Installation requirements for structural bolting assemblies are specified in the 2014 *Specification for Structural Joints Using High-Strength Bolts,* prepared by the Research Council on Structural Connections (RCSC, 2014). The RCSC specification is published in its entirety, without modification, in the American Institute of Steel Construction (AISC) *Steel Construction Manual, AISC-360*. The content of the RCSC Specification is also adapted, edited, and published in other forms, most notably as part of the American Association of State Highway and Transportation Officials (AASHTO) *Fourth Edition, LRFD Bridge Construction Specifications* (AASHTO, 2017).

Practitioners who utilize either *AISC-360* or the AASHTO *Fourth Edition LRFD Bridge Construction Specifications* have four standardized installation methods available to ensure that the minimum acceptable bolt tension is achieved in structural bolting assemblies when minimum bolt tension is required. These methods include Turn-Of-Nut, Calibrated Wrench, Twist-Off Tension-Control Bolt, and the Direct-Tension-Indicator. When a minimum tension is specified it is taken as 70 percent of the minimum axial tensile strength of bolts as specified by ASTM F3125 for Grade[1] A325 and Grade A490 bolts with UNC threads rounded to the nearest kip (Table 1).

Table 1. Minimum Required Bolt Tension*

Bolt Size (inch)	Grade A325 (kips)	Grade A490 (kips)
0.5	12	15
0.625	19	24
0.75	28	35
0.875	39	49
1.0	51	64
1.125	56	80
1.25	71	102
1.375	85	121
1.5	103	148

*Table 11.5.5.4.1-1 from AASHTO's Fourth Edition LRFD Bridge Construction Specifications

[1] The references to Grade A325 and Grade A490 reflect the 2015 publication of ASTM F3125 as a replacement document for ASTM A325, ASTM A490, and other structural bolting standards.

This work focuses on requirements for the Turn-of-Nut and Direct-Tension-Indicator methods in accordance with the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Construction Specifications, Fourth Edition, inclusive of interim updates. This study evaluates and compares the actual tension and deformation achieved in structural bolting assemblies using the Turn-of-Nut method and Direct-Tension-Indicator method. The effects of additional requirements, such as assemblies remaining capable of threading over the full length of the bolt after testing, on the acceptance of assemblies and implications for the range of pretensions that will be developed in the field are also analyzed.

1.1 Installation methods for Structural Bolting assemblies

The Turn-of-Nut and Direct-Tension-Indicator installation methods are described in this section.

1.1.1 Turn-of-Nut installation method

As stated in AASHTO's *Fourth Edition LRFD Bridge Construction Specifications* [AASHTO, 2017], the Turn-of-Nut method requires each snug-tight bolt to be rotated the specified amount shown in Table 2 for non-sloping surfaces. During the Turn-of-Nut tensioning operation it is critical that there be no rotation of the part not turned by the wrench. The tolerances on the rotations are minus 30^o and plus 60^o. The AASHTO commentary notes the tolerances are generous and are both plus and minus because bolt tension in the inelastic range is not very sensitive to rotation. RCSC sets the tolerance for bolts installed by 1/2 turn or less to plus or minus 30^0. For bolts installed by 2/3 turn the plus tolerance increases to plus or minus 45^o. The RCSC commentary notes that strain-control that reaches the inelastic region of bolt behavior is inherently more reliable than a method that is dependent on torque control. The commentary statements from both specifications imply that tension in the inelastic region is a desired end result of the tensioning process.

The snug condition is defined as having all plies of the connection in firm contact, and ten percent of the minimum required tension is assumed to bring the connection to a snug condition. The Turn-of-Nut method is described in the commentary statements from both specifications as a strain-controlled method. However, the final bolt tension is dependent on the initial bolt force in the snug condition [Struik, et al., 1973, Rumpf and Fisher 1963, Sterling, et al., 1965]. Neither the RCSC nor the AASHTO specification include provisions for rejecting structural bolting assemblies that have been tightening using an angle that exceeds the specified 'nut rotation' other than that based upon the authority of the engineer/inspector to order bolts removed due to excessive stick-through. In other words, "over-tightening" is not a consideration when the Turn-of-Nut method is used.

Table 2. Nut Rotation from the Snug Condition for Inch Series Fasteners*

Bolt length measured from underside of head to end of bolt	Required rotation
Up to and including four diameters	⅓ turn
Over four diameters, but not exceeding eight diameters	½ turn
Over eight diameters, but not exceeding 12 diameters	⅔ turn

* Adapted from Table 11.5.5.4.1-2 from AASHTO's Fourth Edition LRFD Bridge Construction Specifications

1.1.2 Direct-Tension-Indicator Installation Method

Direct Tension Indicators (DTIs) are single-use washers with protrusions on one face. The protrusions on the DTI create a gap which decreases in size as the protrusions are flattened due to clamping forces resulting from bolt tightening. The bolting assembly is considered adequately tightened when a specified number of the gaps refuse a 0.005-in. tapered feeler gauge. The specified number of feeler gauge refusals is listed in Table 3 in the column *Minimum Installation Refusals*. AASHTO construction installation specifications state the DTI must be installed either under the head of the bolt, under the turned element provided a washer is used, or in accordance with the manufacturer's recommendations. The connection must first be snugged, but not so much as to crush more than half of the protrusions to less than 0.005 in. during snug tightening. (See Table 3 under *Maximum Verification Refusals*).

The AASHTO DTI method includes prohibitions against 'over-tightening'. Specifically, if any structural bolting assembly is tensioned so that no visible gap in any space remains, the bolt assembly, including the DTI, shall be removed and replaced by a new properly tightened bolt assembly and DTI. The RCSC Specification does not include prohibitions on 'over-tightening' for any of the four standardized installation methods. The RCSC Specification states for each of the methods: "*A pretension that is greater than the value specified in Table 8.1* [Table 1 of this work] *shall not be cause for rejection*."

Table 3. Direct Tension Indicator Requirements*

DTI Spaces	**Maximum Verification Refusals**		**Minimum Installation Refusals**	
	Coated DTIs under turned element	All other cases	Coated DTIs under turned element	All other cases
4	3	2	3	3
5	4	2	4	3
6	5	3	4	3
7	6	3	6	4
8	7	4	7	5
9	8	4	8	5

*Table 11.5.5.4.6a-1 from AASHTO's Fourth Edition LRFD Bridge Construction Specifications

1.2 Qualification Requirements for Structural Bolting Assemblies

Structural bolting assemblies must undergo qualification testing prior to being used for projects to verify that the method being used can develop sufficient tension in the bolt. These procedures are described in the following subsections. Required Structural Bolting Assembly testing includes Rotational Capacity (RC) tests of the nut, washer, and bolt combination to be used following the procedures of ASTM F3125 Annex 2 (ASTM 2015). This procedure demonstrates that the assembly can withstand additional rotation beyond normal installation without bolt failure or thread stripping. A requirement for Rotational-Capacity Testing of assemblies including captive DTIs was included in the *Third Edition AASHTO LRFD Bridge Construction Specification*, but was removed in the Fourth Edition.

1.2.1 (Pre-Installation) Verification Testing for Turn-of-Nut Installation

Section 11.5.6.4.4 of the *AASHTO LRFD Bridge Construction Specifications* describes the requirements for verification testing of assemblies installed with the Turn-of-Nut method. Using a device capable of indicating bolt tension the crew shall demonstrate the method being used can produce a snug condition in the assembly and that the number of turns from snug can be controlled to produce a tension of at least five percent greater than the required tension. Three verification repetitions are required for each diameter, length, and grade of bolt used in the work. Although not stated in the Turn-of-Nut Verification section of the AASHTO Specifications, it is commonly accepted that a change in the lot number for any component in the assembly verification testing requires additional testing such that every lot combination to be used on the project is tested. Section 7 of the RCSC Specification describes similar requirements for Pre-Installation Verification Testing.

1.2.2 (Pre-Installation) Verification Testing for Direct Tension Indicator Installation

Sections 11.5.5.4.6 and 11.5.5.4.6a of the *2017 AASHTO LRFD Bridge Construction Specifications* describes the requirements for verification testing of assemblies with DTIs and requires three tests without failure. The fastener assembly shall be installed in the tension-measuring device with the DTI located in the same position as in the work. The bolt is first tensioned to the verification tension (5% above the tension listed in Table 1). If an impact wrench is used, the tension developed using the impact wrench shall be no more than two-thirds of the required tension. Subsequently, a manual wrench shall be used to attain the required tension. The number of refusals of a 0.005-in. feeler gage is recorded and should not exceed the number listed in Table 3 under *Maximum Verification Refusals.* Test failure occurs if the Maximum Verification Refusals is exceeded at the minimum required tension. The bolt is further tightened until all of the gaps are closed to a 0.005-in. feeler gage and a visible gap exists in at least one space. The load at this condition is recorded and the bolt is removed from the tensioning device for an additional inspection. The nut shall be able to be "*run down by hand for the complete thread length of the bolt excluding the thread run-out."* If the nut cannot be run down the full length of the thread the test is considered a failure unless the load recorded is less than 95% of the average load measured in the rotational capacity tests. A failed test indicates the combination of test parameters is not acceptable. The RCSC Specification does not include any requirements comparable to the bolt thread check required by AASHTO for the DTI method.

2.0 Test Program

The test program included both Grade A325 and Grade A490 bolting assemblies. Bolting assemblies included 3/4-in., 7/8-in., and 1-in. diameters. Bolting assemblies included some that were plain finish (Type 1), mechanically galvanized (MG), or weathering steel (Type 3). Bolting assemblies from two different manufacturers were used, and DTIs from two different manufacturers were used.

Mechanical testing was performed using two different procedures and machines. In one test procedure the load was increased continuously and in the second type the load was increased incrementally. The continuous testing was performed using an instrumented Skidmore-Wilhelm bolt tension calibrator with continuous measurement of bolt tension, rotation, and applied torque. In these tests, rotations were measured to approximately 420 degrees and 240 degrees, depending on the test. No measurements of the gaps were conducted in the continuous tests. In the other tests a Skidmore-Wilhelm bolt tension calibrator was used with load applied incrementally to allow the closure of DTI spaces to be monitored with a 0.005-in. feeler gage. The number of spaces open was recorded at each load increment. In all cases the nut was the turned element. In tests with DTIs, the DTI was under the nut and a hardened washer, with the protrusions facing the hardened washer. The incrementally loaded tests were conducted to a rotation of at least 90 degrees past the point at which all of the gaps were closed, as defined by not admitting the 0.005-in. feeler gage. Table 4 provides a summary of the tests and number of repetitions. The bolt length for the 3/4-in. diameter bolts was 3.0 inches and for the 7/8-in. and 1.0-in. bolts the length was 3.25 inches. The load-rotation curves from the continuous and incremental tests are presented in Figures 1 through 11. Tests results from assemblies with DTIs from both manufacturers are shown in these figures.

Table 4. Summary of Testing Program

Assembly	**Bolt Dia. (inch)**	**Grade**	**Bolt Manufacturer**	**# Repetitions continuous rotation w/o DTI**	**# Repetitions continuous rotation w/DTI***	**# Repetitions incremental loading with DTI**
1	3/4	A325-1	A	3	3	5
2	3/4	A325-1	B	2	4	6
3	7/8	A325-1	B	3	4	6
4	7/8	A325-3	A	3	4	6
5	7/8	A325-3	B	2	4	6
6	7/8	A325-MG	A	3	4	6
7	7/8	A325-MG	B	2	4	6
8	7/8	A490-1	A	3	4	4
9	7/8	A490-1	B	2	4	5
10	1	A325-1	A	3	4	5
11	1	A325-1	B	2	4	6

*Typically two repetitions each with DTIs from two manufacturers

In addition to tests described in Table 4, tests were performed to determine the tensile load at which the nut could not be run the full length of the bolt. Three bolts from each lot were used. The first bolt was tightened in the bolt tension calibrator to a load slightly below the transition from linear to nonlinear behavior, which was identified from the previous continuous tests. The bolt was removed from the calibrator and then the nut was successfully run the full length of the thread in all cases. A second bolt was tightened to the previous load and then an additional 30^0 rotation was applied. The resulting load was noted and the bolt was removed from the calibrator and checked to determine if the nut could be run the full length of the thread. If a nut could be run the full length of the second bolt, a third bolt was tightened to the same load as the first bolt and then an additional 60^0 rotation was applied. If a nut could not be run the full length of the second bolt, then a 15^0 increment past the load from the first bolt was used for the third bolt. The third bolt was then checked to determine whether the nut could be run the full length of the thread. For all lots, the three-bolt sequence identified a load at which the nut could not be run the full length of the thread.

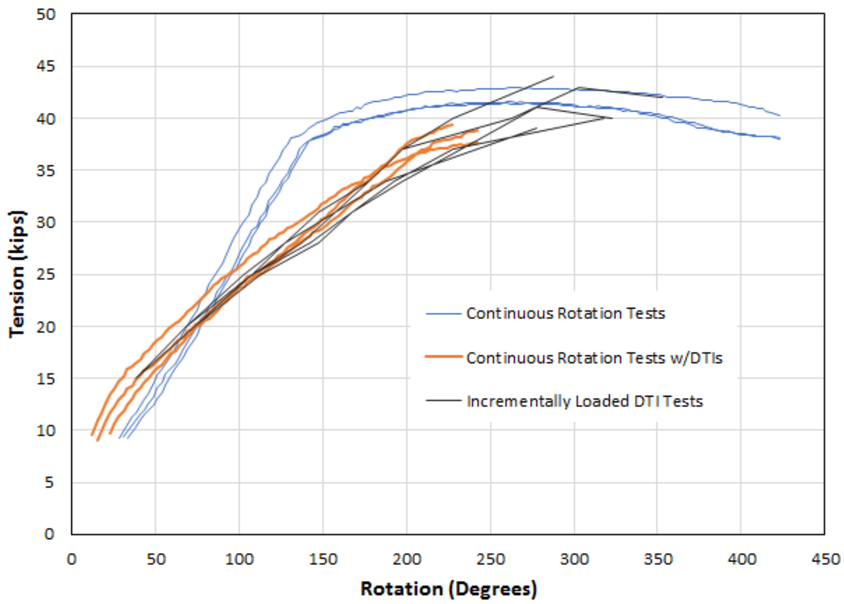

Figure 1. Comparison of continuous and incremental data recorded from 3/4-in. diameter Grade A325-1 assemblies (Bolt Manufacturer A) with and without DTIs.

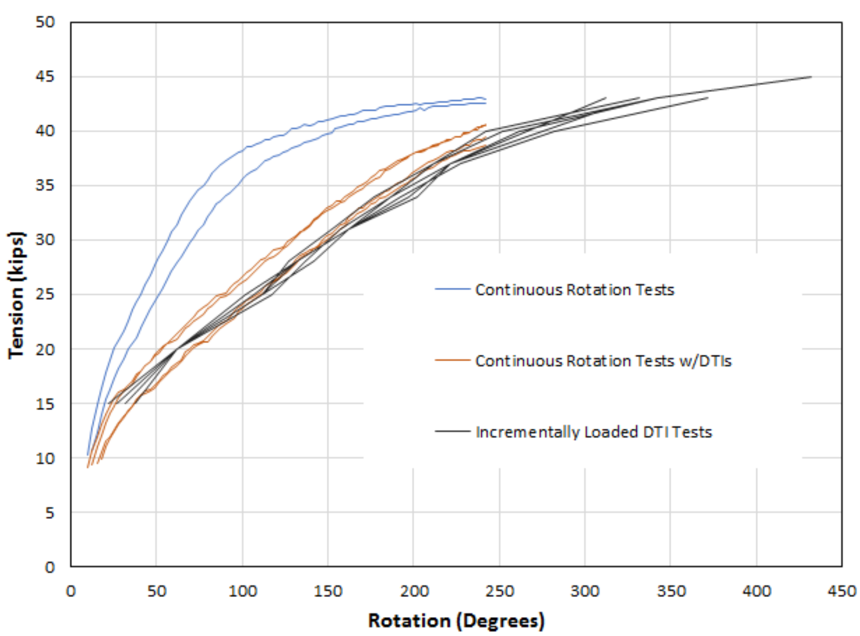

Figure 2. Comparison of continuous and incremental data recorded from 3/4-in. diameter Grade A325-1 assemblies (Bolt Manufacturer B) with and without DTIs.

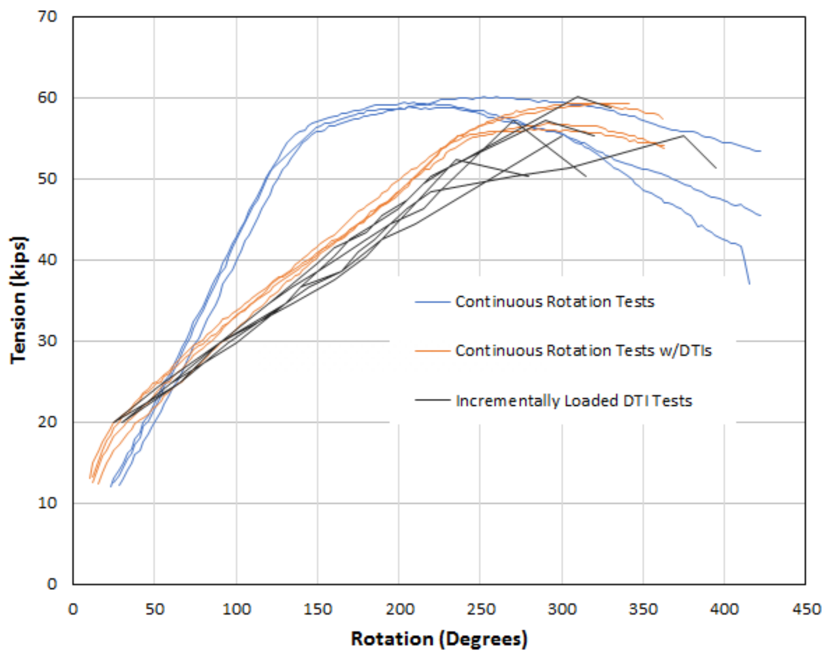

Figure 3. Comparison of continuous and incremental data recorded from 7/8-in. diameter Grade A325-1 assemblies (Bolt Manufacturer B) with and without DTIs.

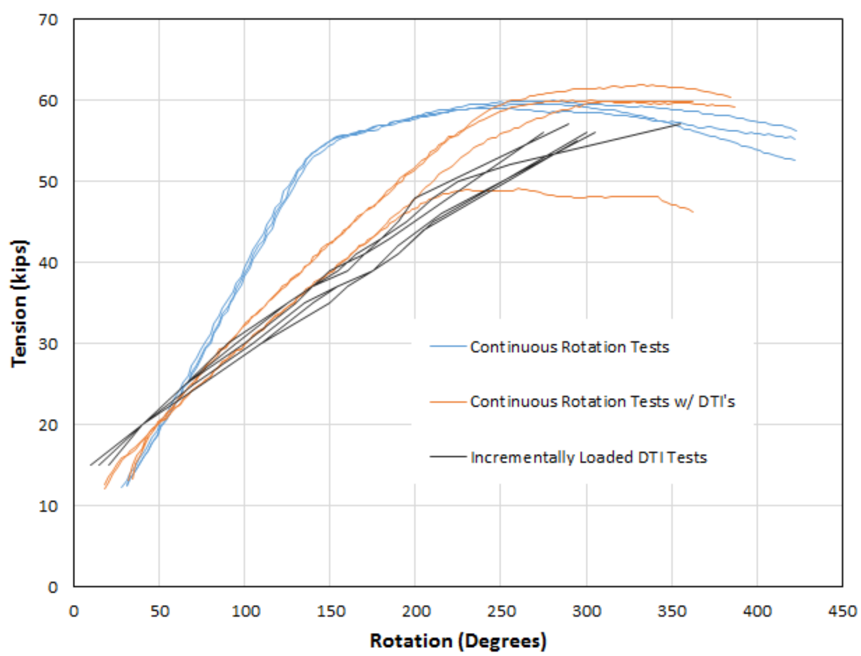

Figure 4. Comparison of continuous and incremental data recorded from 7/8-in. diameter Grade A325-3 assemblies (Bolt Manufacturer A) with and without DTIs.

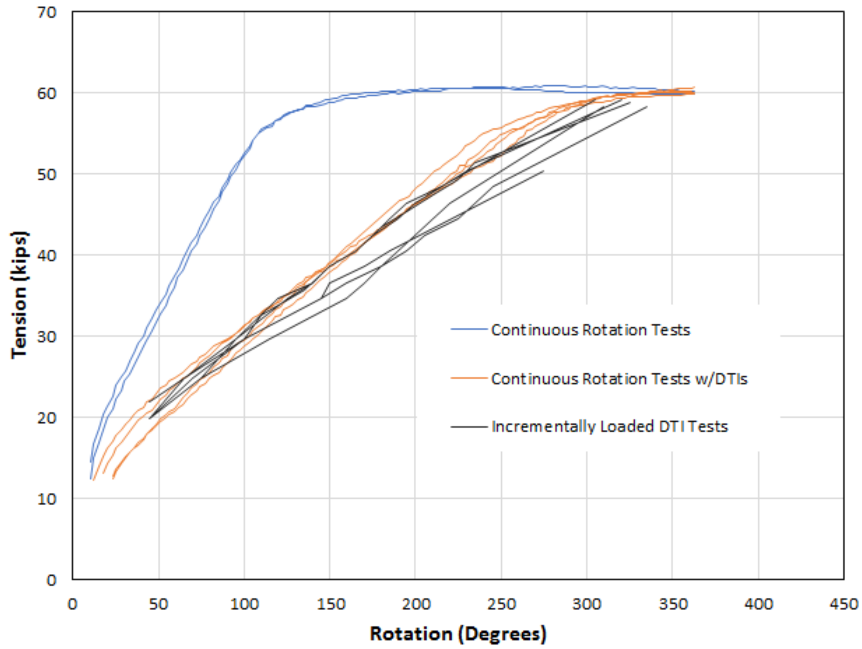

Figure 5. Comparison of continuous and incremental data recorded from 7/8-in. diameter Grade A325-3 assemblies (Bolt Manufacturer B) with and without DTIs.

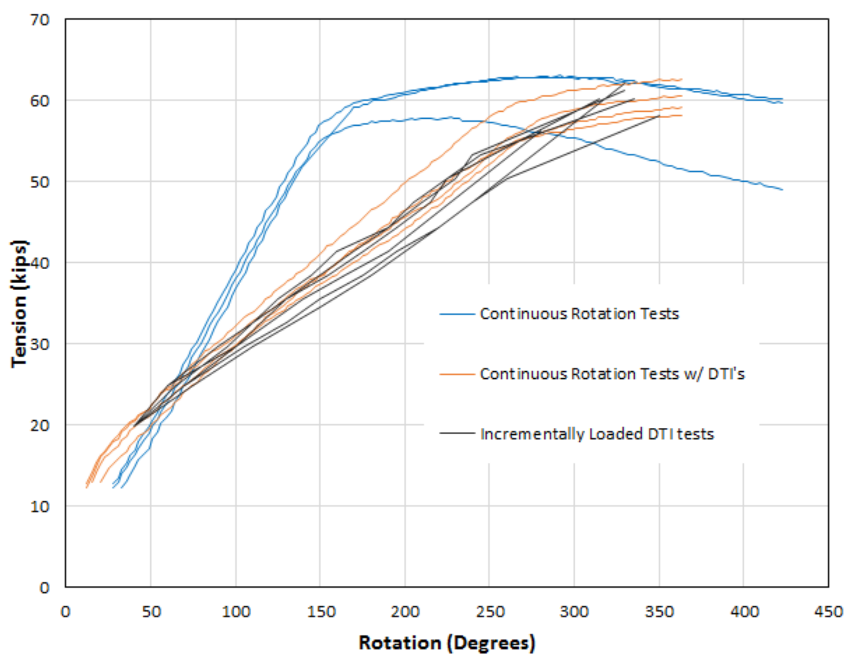

Figure 6. Comparison of continuous and incremental data recorded from 7/8-in. diameter Grade A325-MG assemblies (Bolt Manufacturer A) with and without DTIs.

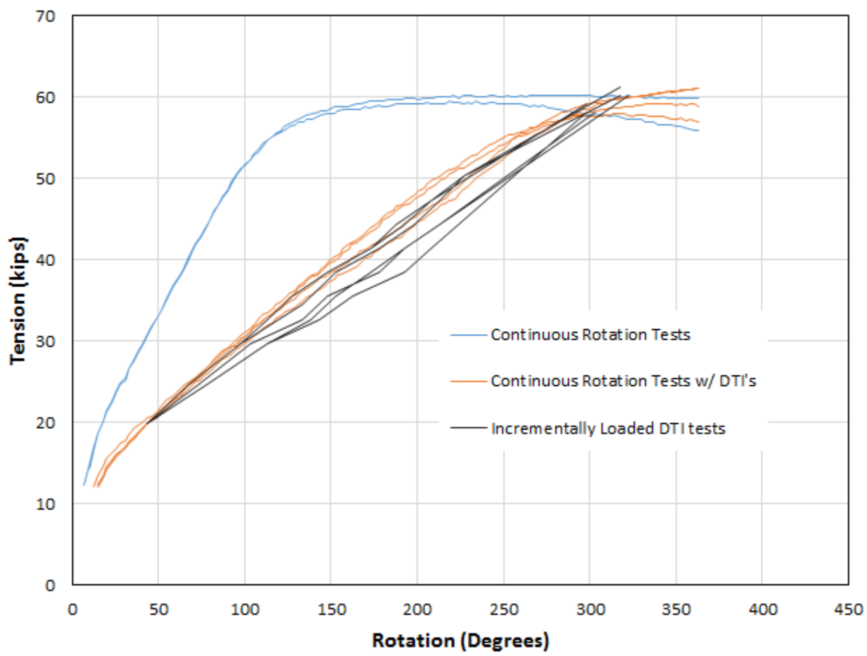

Figure 7. Comparison of continuous and incremental data recorded from 7/8-in. diameter Grade A325-MG assemblies (Bolt Manufacturer B) with and without DTIs.

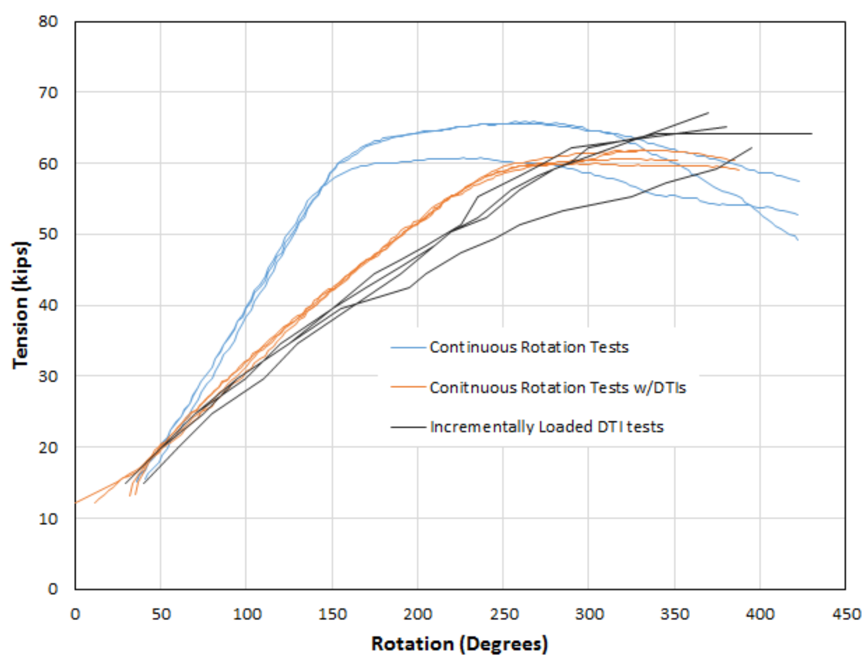

Figure 8. Comparison of continuous and incremental data recorded from 7/8-in. diameter Grade A490-1 assemblies (Bolt Manufacturer A) with and without DTIs.

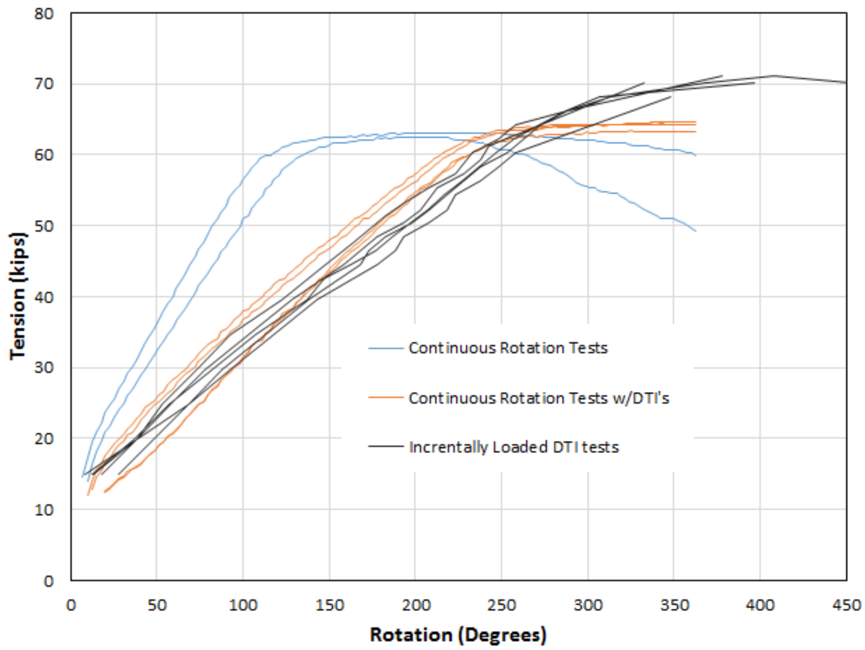

Figure 9. Comparison of continuous and incremental data recorded from 7/8-in. diameter Grade A490-1 assemblies (Bolt Manufacturer B) with and without DTIs.

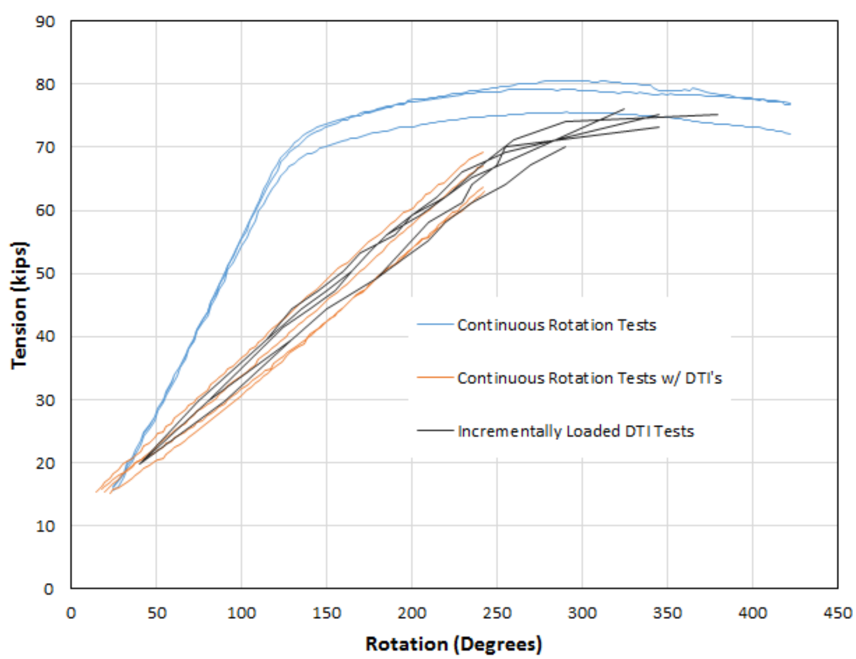

Figure 10. Comparison of continuous and incremental data recorded from 1-in. diameter Grade A325-1 assemblies (Bolt Manufacturer A) with and without DTIs.

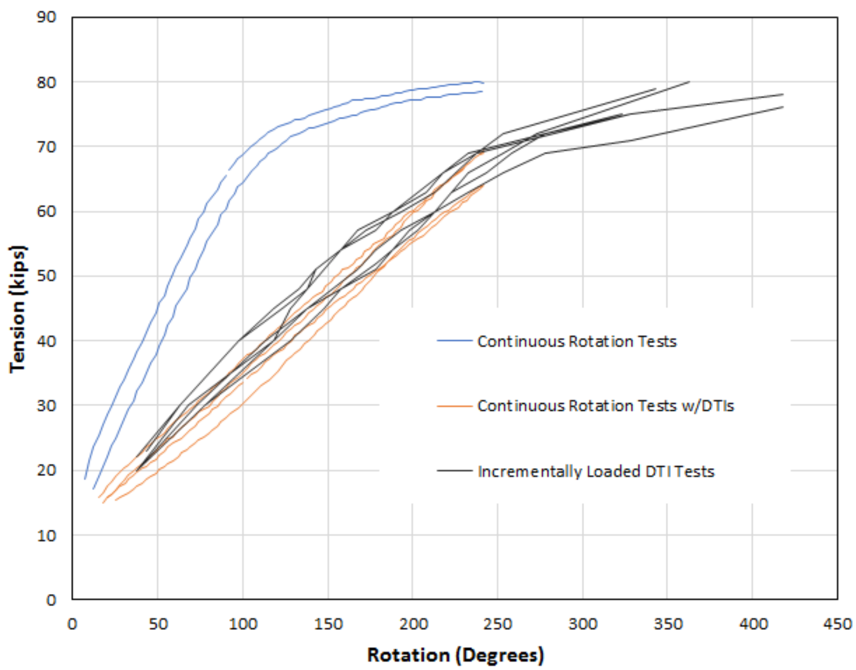

Figure 11. Comparison of continuous and incremental data recorded from 1-in. diameter Grade A325-1 assemblies (Bolt Manufacturer B) with and without DTIs.

3.0 Results and Discussion

The data from the tests described in Section 2.0 were analyzed and are discussed in Sections 3.1 and 3.2.

3.1 Comparison of load and deformation achieved with Turn-of-Nut method and DTI method

The load level and deformation of bolt assemblies tightened using the Turn-of-Nut method and using the Direct-Tension-Indicator method can be compared. The data from the continuous rotation testing and the incremental load testing of assemblies with DTIs were used to make these comparisons, and are shown in Figures 12 through 33. These figures include the continuous tension-rotation curves established for each assembly with and without DTIs as well as additional points, lines and shading to compare the two methods of establishing minimum bolt tension. The following paragraphs describe how these figures were established and the information contained within them.

First, the load at "snug" condition without DTIs was defined, and the corresponding rotation on the non-DTI tension-rotation plots was identified. The specified Turn-of-Nut rotation was then added to the rotation corresponding to the snug condition, and the tension-rotation curves were used to determine the corresponding tension that would be achieved in the assembly for the snug condition plus Turn-of-Nut rotation. Additional points were determined to indicate the upper tolerance of the Turn-of-Nut rotations. For the length-to-diameter ratios used in these tests the specified rotation is 1/3 rotation (120^0) and the tolerance is $+60^0/-30^0$.

When the Turn-of-Nut method is used, the resulting bolt tension is highly dependent upon the starting tension at the snug condition. Snug tight is defined as occurring when all of the plies of a connection are in firm contact. There is no specified tensile load for snug tight and the established definition is commonly stated as the tension achieved by the full effort of a worker using a common spud wrench or the tension achieved with a few impacts of an impact wrench [RCSC, 2014]. For this study, two definitions of snug have been considered. The first defines snug as 10% of the required pretension and is based on the Rotational Capacity Test requirements of ASTM F3125. The second definition of snug was established through a review of available literature and limited laboratory testing. In an experimental study Murray, et al. [1991] measured the tension developed in the snug condition as an average of 10.7 kips for 3/4-in. diameter bolts and 13.5 kips for 1-in. diameter bolts. Fleischman, et al. [1991] found the average tension was approximately 15 kips for 3/4-in., 20.5 kips for 7/8-in., and 27 kips for 1-in. diameter. Kulak, et al., (2001) present data for 7/8-in. diameter A325 bolts showing an average snug condition of 26 kips. In our own labs, two individuals used a torque wrench to determine the "full-effort" torque they could apply to an assembly that included a hardened washer. One individual achieved 240 in.-lb and the other 400 in.-lb, indicating there is significant variability from person to person. These torque values were compared to the continuous tension-torque-rotation data for each assembly to determine a realistic range of tensions resulting from a snug condition. Table 5 shows the approximate range of tensions in the tests performed for this study that correspond to each of these torques. The tension achieved with an equivalent torque would be lower in a bolting assembly that does not include a hardened washer behind the nut. Based upon these tests, those presented by Kulak, and the work of Murray, et al. and of Fleischman, et al., a tension load of 20 kips for 7/8-in. diameter and 1-in. diameter bolts and 15 kips for 3/4-in. diameter for the snug condition was established. These values are more representative of an individual's full effort compared to the arbitrary 10% of the required pretension, and are therefore more realistic values of the tension associated with the snug condition.

As previously described in the Test Program section, assemblies with DTIs were tightened with small increments of load while checking for DTI gap closure after each increment to determine the average load at which at least half and all of the DTI gaps were closed. After all of the gaps were closed an additional 90^0 rotation was applied to the nut and the load recorded. Additional tests were performed to determine the approximate load value at which a nut could no longer be run by hand up the full length of the bolt.

Table 5. Tension corresponding to torque from continuous rotation tests.

Bolt Diameter (inch)	Torque (in.-lb)	Tension (kips)
0.75 Type 1	240	20-24
0.75 Type 1	400	39-40
0.875 Type 1 and 3, A325	240	20-22
0.875 Type 1 and 3, A325	400	32-42
0.875 MG A325	240	25-30
0.875 MG A325	400	45-50
0.875Type 1 A490	240	15-20
0.875 Type 1 A490	400	30-35
1.0 A325 Type 1	240	15-17
1.0 A325 Type 1	400	25-30

Figures 12 through 33 provide a comparison between the tension loads and rotation resulting from use of Turn-of-Nut tensioning and use of Direct Tension Indicators. There are two figures for each series of assembly – one for each definition of snug condition. Each series of structural bolting assembly consists of a nut, bolt, and washer taken from the same lots. The load data from the DTI tests is the average of the incremental tests in Table 4 using DTIs from two manufacturers. Each figure shows the continuous tension-rotation curves for the assembly with and without DTIs. Closed symbols are used to indicate the superimposed snug condition and the tension achieved at the specified Turn-of-Nut rotation and at that rotation plus the tolerance. Horizontal lines indicate the load at which half of the DTI gaps were closed and all of the DTI gaps were closed. A shaded region indicates the load at which the assembly transitions to a condition in which the nut cannot be run the full length of the thread.

The results of these tests show that for all of the cases studied, the Turn-of-Nut method with snug defined as 10% of the of the required pretension listed in Table 1 resulted in a bolt tension above the required tension and usually within the linear range of the bolt behavior. However, when a more realistic snug condition was defined as 15 kips for 3/4-in. diameter bolts and 20 kips for 7/8-in. and 1.0-in. diameter bolts, the resulting bolt tension was into the nonlinear region of the load-deformation behavior. In addition, under the more realistic snug condition the Turn-of-Nut method frequently resulted in a bolt tension that was at or above the range of loads determined to result in a condition in which the nut could not be run the full length of the threads.

The lowest expected load for assemblies with Direct Tension Indicators is the load that will exactly cause half (in cases with even number of gaps) or just more than half (in cases with an odd number of gaps) to close, as defined by rejecting the feeler gage. However, in practice the tension resulting from installation will be somewhat higher than the lowest expected load. The lowest expected load for assemblies with Direct Tension Indicators always resulted in a bolt tension above the minimum required and lower than the tension produced by the Turn-of-Nut method using the specified rotation – regardless of how the snug condition was defined. For the 3/4-in. diameter bolts, the load at which all of the DTI gaps were closed was usually above the region identified as the transition to the nut no longer capable of being run the length of the bolt. However, this load was below the tension achieved using the Turn-of-Nut method from a realistic snug condition. For all of the 7/8-in., A325 tests the load at which all of the spaces were closed was well below the transition region where the bolt is no longer capable of being rethreaded and below the tension achieved using the Turn-of-Nut method from either snug condition. For the 1-in. diameter tests the load at which all of the spaces were closed was well above the transition region to the nut no longer capable of being run the length of the bolt and approximately the same as or below the tension achieved using the Turn-of-Nut method from either snug condition.

For the A490 bolted assemblies, the Turn-of-Nut method with either definition of snug results in loads greater than the required pretension. Using bolts from manufacturer A and the 10% definition of snug, the turn-of-nut method results in a load that is still in the linear region. For the remaining cases, the Turn-of-Nut method results in a load that is either within or above the transition to the region in which the nut could no longer be run the length of the bolt thread. The load at which just more than half of the DTI gaps are closed is within the linear region for all cases, while the load at which all of the DTI gaps are closed is at the upper range or above the transition to the region in which the nut could no longer be run the length of the bolt thread. Incremental load tests on one manufacturer of DTIs resulted in loads that were greater than those developed during the continuous load tests. It is possible this is the result of plastic cyclic hardening occurring in the cycles of applying torque to increase load, followed by some relaxation of the bolt while the gap spacing is being checked. Note that, while the results differ between assemblies with the two different DTI manufacturers, a DTI is not able to alter the ultimate strength of a bolt.

The results presented in Figures 12 through 33 can also be used to identify and compare the lowest expected bolt tension achieved using the Turn-of-Nut method and the Direct-Tension-Indicator method. The lowest expected load using the Turn-of-Nut method is produced if the angle measurement begins from the 10% pretension condition and the specified rotation minus the 30^0 tolerance is applied. This load is not marked in the figures but can be found in the figures for which snug is defined as 10% of the pretension. The triangle symbol in these figures marks the specified rotation. By moving 30^0 to the left on the rotation axis, one can determine the minimum expected load when the Turn-of-Nut method is used. The lowest expected load when the Direct-Tension-Indicator method is used is marked by the horizontal line indicating at least half of the protrusion gaps are closed to the 0.005-in. feeler. The resulting minimum expected loads for both installation methods are shown in Table 6. In most cases the minimum expected load is fairly similar for both methods, with each method resulting in the higher load in approximately the same number of cases.

Table 6. Comparison of minimum expected load.

Assembly	Bolt Dia. (inch)	Grade	Bolt Manufacturer	Minimum Expected Load (kips)	
				Turn-of-Nut Method	Direct-Tension-Indicator Method
1	3/4	A325-1	A	27.5	32.2
2	3/4	A325-1	B	35.9	34.1
3	7/8	A325-1	B	38.9	43.9
4	7/8	A325-3	A	38.8	39.3
5	7/8	A325-3	B	49.8	40.0
6	7/8	A325-MG	A	38.1	42.5
7	7/8	A325-MG	B	49.5	42.0
8	7/8	A490-1	A	37.7	52.1
9	7/8	A490-1	B	52.0	51.6
10	1	A325-1	A	55.3	63.4
11	1	A325-1	B	65.7	62.5

AASHTO requirements for acceptance are not consistent between the Turn-of-Nut and Direct-Tension-Indicator methods. Both methods do address meeting the minimum tension criteria in comparable ways. However, assemblies may be rejected if, following verification testing, the nut cannot be run down the full length of the bolt thread. Bolting assemblies with DTIs are the only ones subjected to a thread test in which the nut must be run by hand for the full length of the bolt thread. This requirement forces manufacturers of DTIs to calibrate so that minimum load requirements are met when half of the gaps are closed to the 0.005-in. feeler gage, yet the bolt must remain in the linear region when all of the gaps are closed. This trend is seen in Figures 12 through 33. The data presented in these figures (represented by shaded blocks) show that assemblies reach a state in which the nut cannot be run for the full length of the thread very early into the nonlinear region of the bolt load curve. However, the commentary material in both AASHTO and RCSC provisions imply that an inelastic state is desired for pretensioned bolts. AASHTO commentary to section 11.5.5.4.6a argues that the thread test is required for DTI verification and no other method because the DTI method is the only force-control method in the code. The commentary suggests with torque-control methods such as calibrated wrench and twist-off bolts, the torque setting of the wrench or the twisting off of the spline limit the load on the bolt. In the Turn-of-Nut method, identified as a strain-control method, the fastener assembly is tested to beyond the installation tolerance during rotational capacity testing. The additional thread test requirement for DTIs protects against bolt failure during installation if there is a combination of a weak bolt and strong DTI. The term *strain-controlled* is presumed to mean that the Turn-of-Nut method relies substantially upon the geometry of the fasteners, most notably the thread pitch, and the fact that only steel is permissible in the grip. The Turn-of-Nut method is built upon the assumption that there are no gaps remaining between the steel plies when the specified turn is applied following snug-tightening. In addition, the Turn-of-Nut method is not, per se, dependent upon torque. However sufficient lubrication is presumed to be present to allow tensioning into the inelastic region without the bolt suffering torsional fracture prior to reaching the required turn/tension. The classification of DTIs as a *force-control method* may be due to the fact that DTI protrusions flatten as a result of compressive stress that is corresponds to bolt tension.

The Rotational Capacity Test performed in accordance with ASTM F3125 requires that the threads not strip during the test, but does not require that the nut can be run up and down the full length of the thread. In other words, plastic deformation of the threads and bolt itself is allowed, so long as the threads do not fail. With the publication of ASTM F3125 in 2015, ASTM has updated and relocated its Rotational Capacity Test procedure to Annex A2 of that standard. The ASTM criteria pertaining to thread condition following testing is as follows: The nut shall turn on the bolt threads to the position it was in during the test. The nut does not need to run the full length of the threads. Inability to turn the nut by hand is considered thread failure. ASTM F3125 further notes elongation of the bolt, in the threads between the nut and bolt head, is to be expected and is not to be classified as a failure. However, it is precisely this deformation that prevents a nut from being run past the position it was in during the test (in other words, for the full length of the thread).

One other noted anomaly of Rotational Capacity testing as it relates to the Turn-of-Nut method is that the RC test states in part, *'The RC test shall only apply to matched assembly lots that contain one bolt, one nut, and one or more washers.'* Whereas, Section 6.2 of the RCSC and Clause 11.5.5.4.4 of ASSHTO LRFD do not require the use of washers when the Turn-of-Nut method is used. Rotational Capacity testing on an assembly that includes a hardened washer will not necessarily reflect the behavior of an assembly that does not use a hardened washer, as the absence of a hardened washer will tend to reduce the tension reached for a given rotation.

As shown in Figures 12 through 33, bolting assemblies properly tensioned using Turn-of-Nut methods (denoted by the triangle symbols on the plots) can be expected to have loading into the nonlinear region – a desired condition, regardless of the definition of snug. If these bolts were removed, it is very unlikely the nut could be run by hand for the full length of the thread. A simple change to the AASHTO verification criteria for DTIs would be consistent with the requirements of the ASTM F3125 Rotational Capacity test requirements. Rather than requiring the nut to be run the full length of the thread the criteria should state that, after loading to the refusal of the 0.005-in. feeler gage in all openings, the nut shall be removed and then be turned to the position it was during the test. This change would allow manufacturers to calibrate DTIs to produce the minimum required pretension and take the bolt tension into the desired nonlinear region – consistent with the requirement for bolts installed with the Turn-of-Nut method.

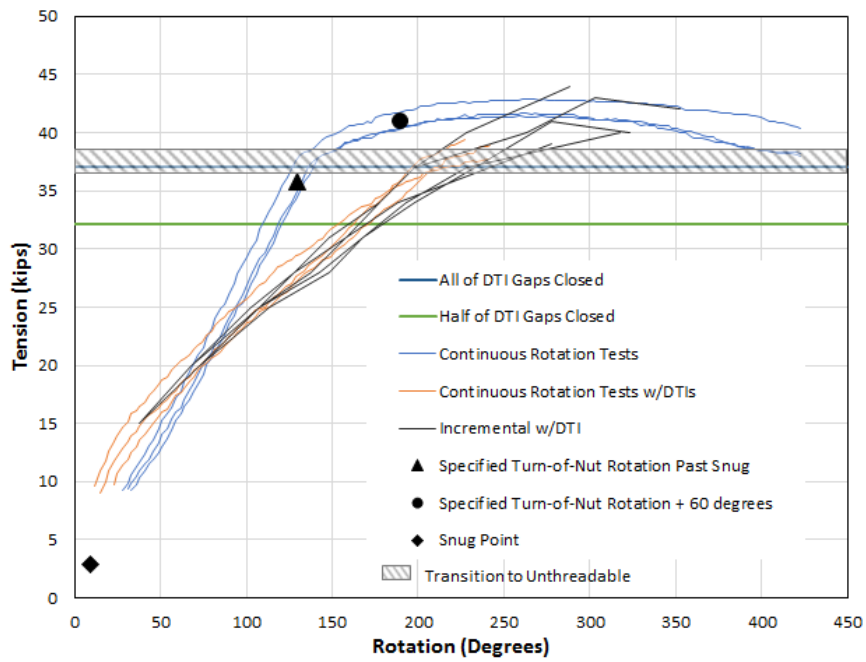

Figure 12. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 3/4-in. diameter, Bolt Manufacturer A, Grade A325 Type 1.

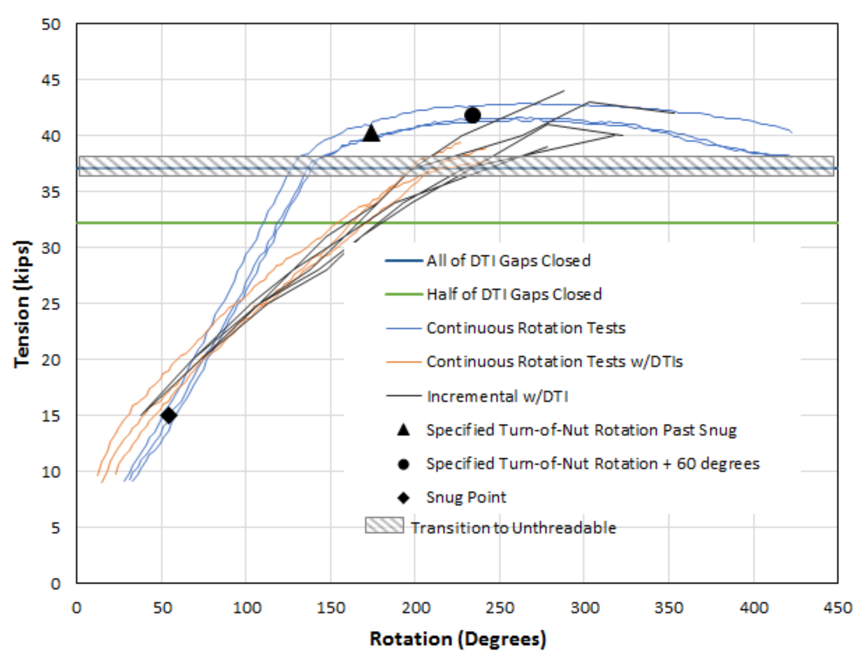

Figure 13. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 15 kips. 3/4-in. diameter, Bolt Manufacturer A, Grade A325 Type 1.

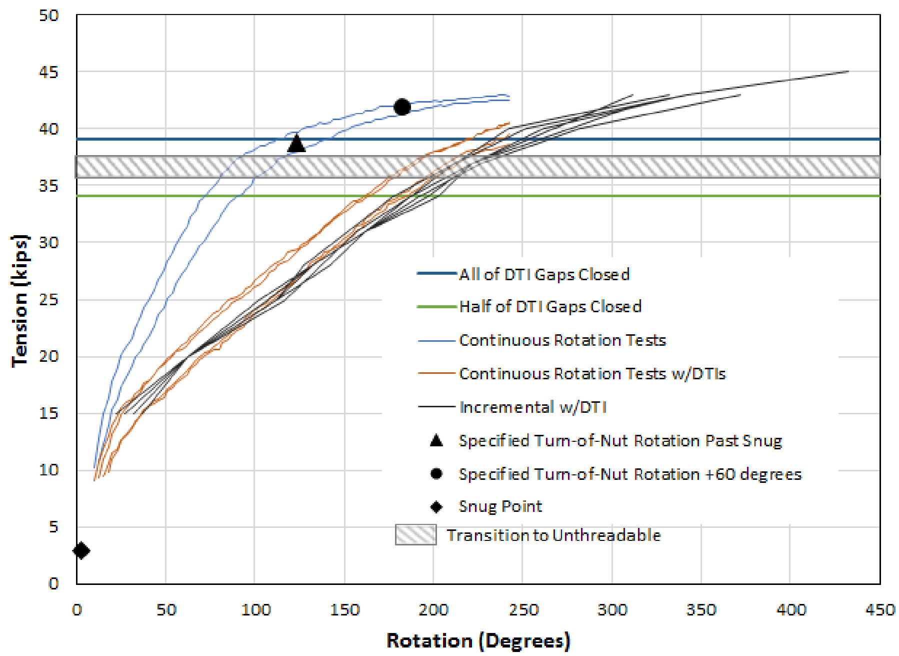

Figure 14. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 3/4-in. diameter, Bolt Manufacturer B, Grade A325 Type 1.

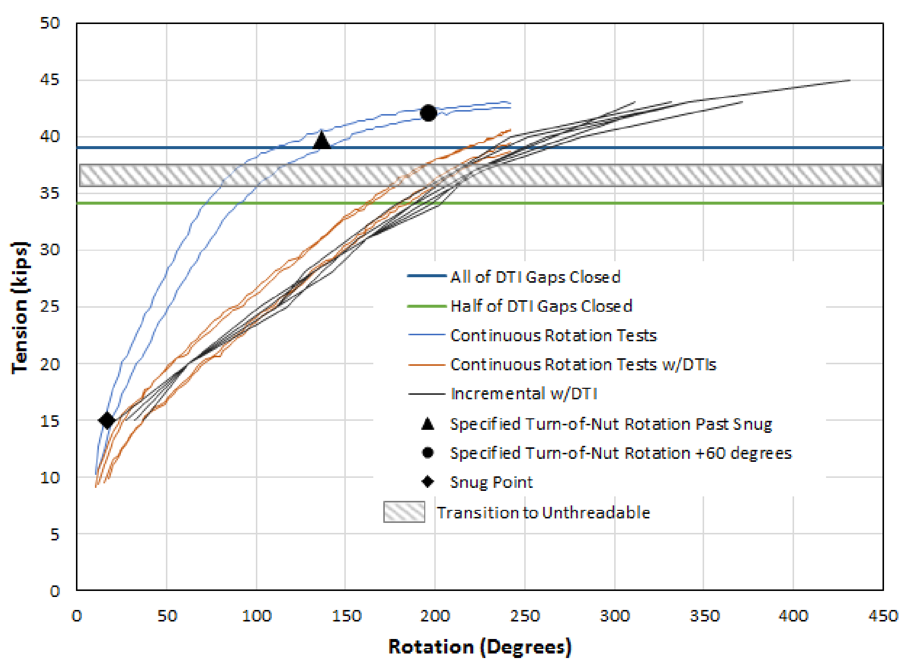

Figure 15. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 15 kips. 3/4-in. diameter, Bolt Manufacturer B, Grade A325 Type 1.

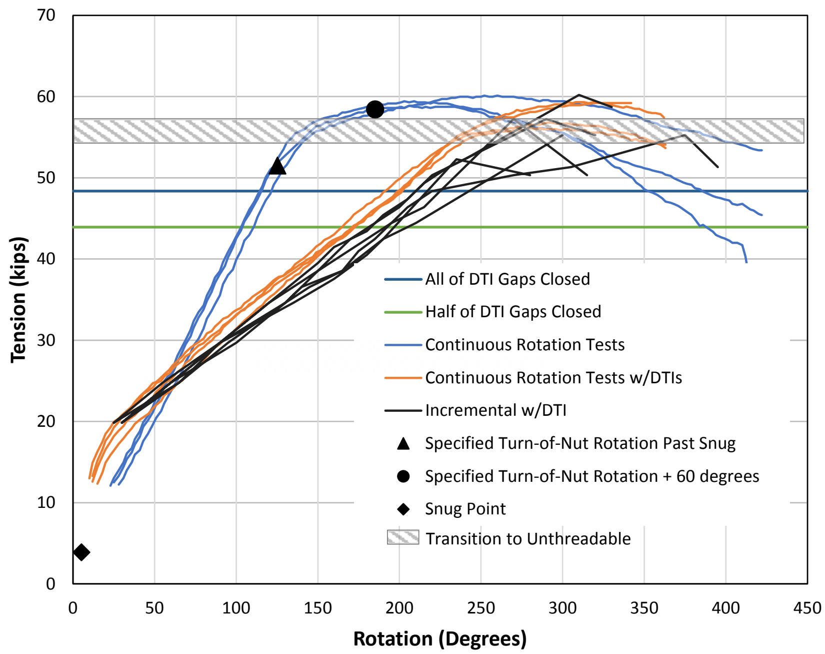

Figure 16. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 7/8-in. diameter, Bolt Manufacturer B, Grade A325 Type 1.

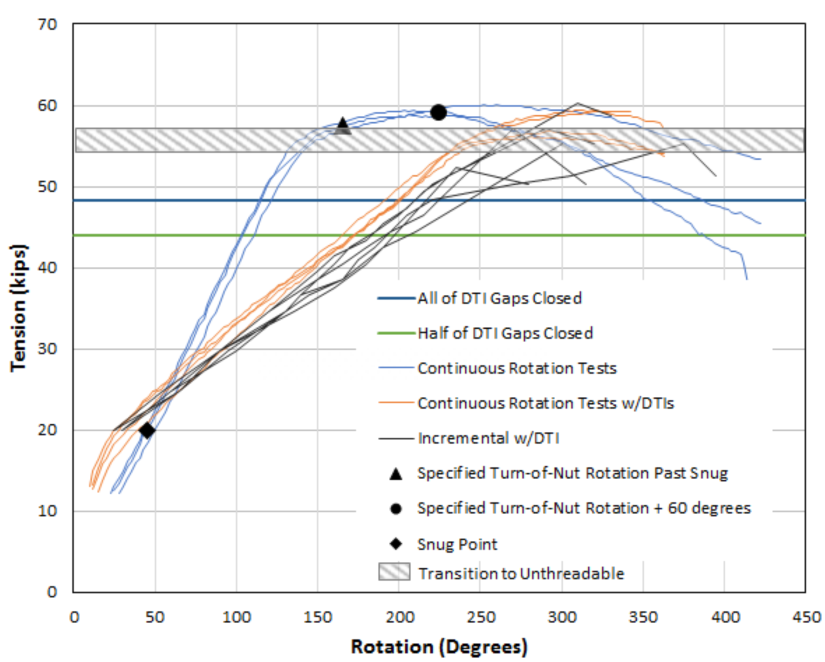

Figure 17. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 20 kips. 7/8-in. diameter, Bolt Manufacturer B, Grade A325 Type 1.

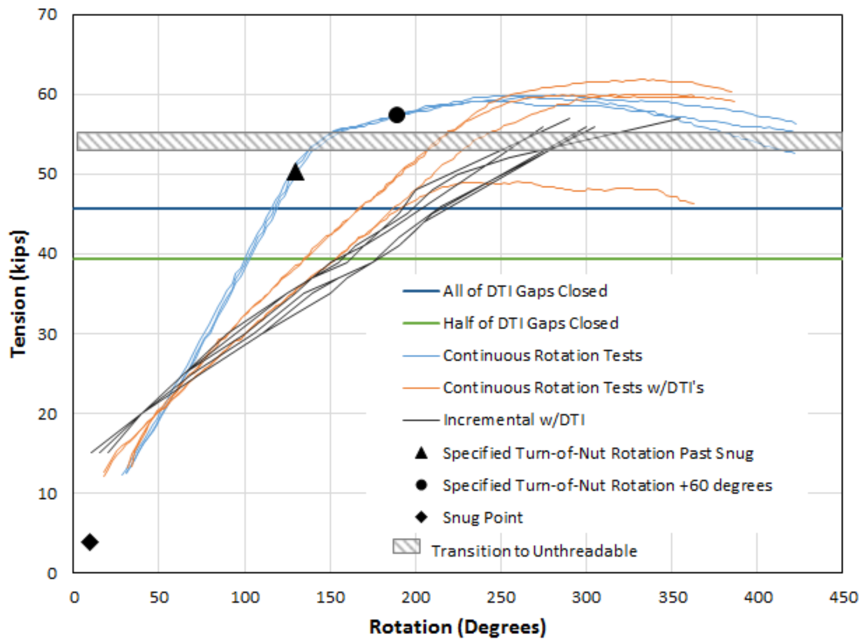

Figure 18. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 7/8-in. diameter, Bolt Manufacturer A, Grade A325 Type 3.

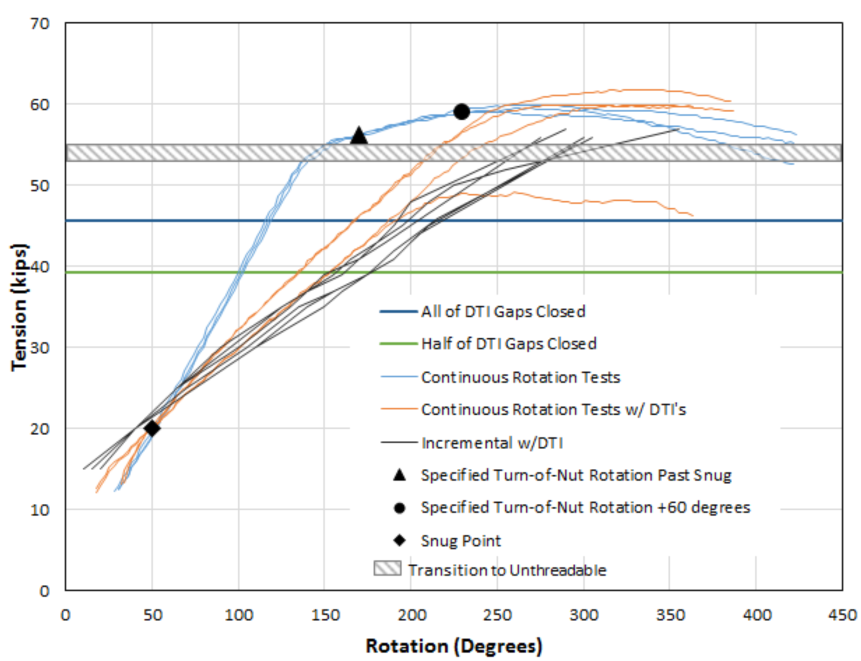

Figure 19. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 20 kips. 7/8-in. diameter, Bolt Manufacturer A, Grade A325 Type 3.

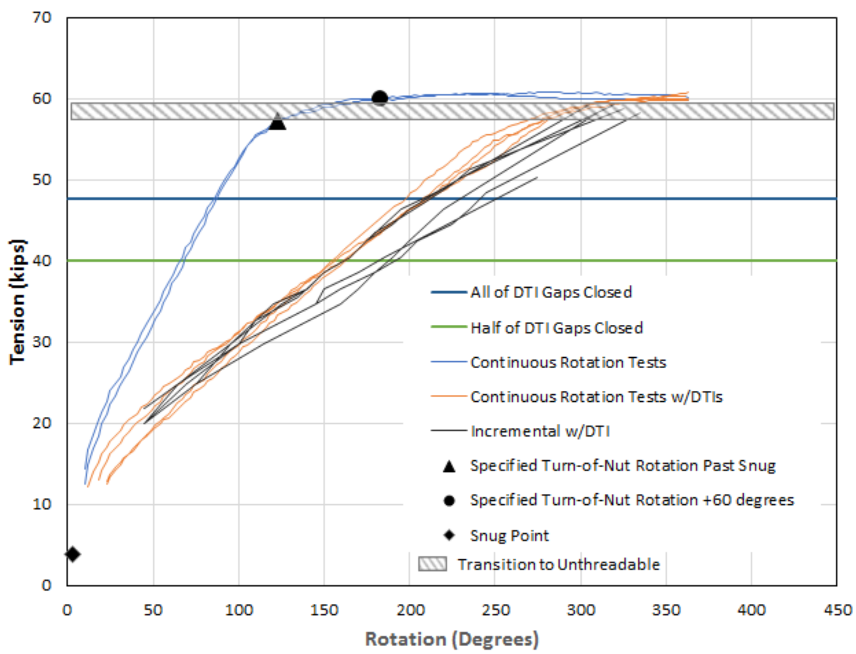

Figure 20. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 7/8-in. diameter, Bolt Manufacturer B, Grade A325 Type 3.

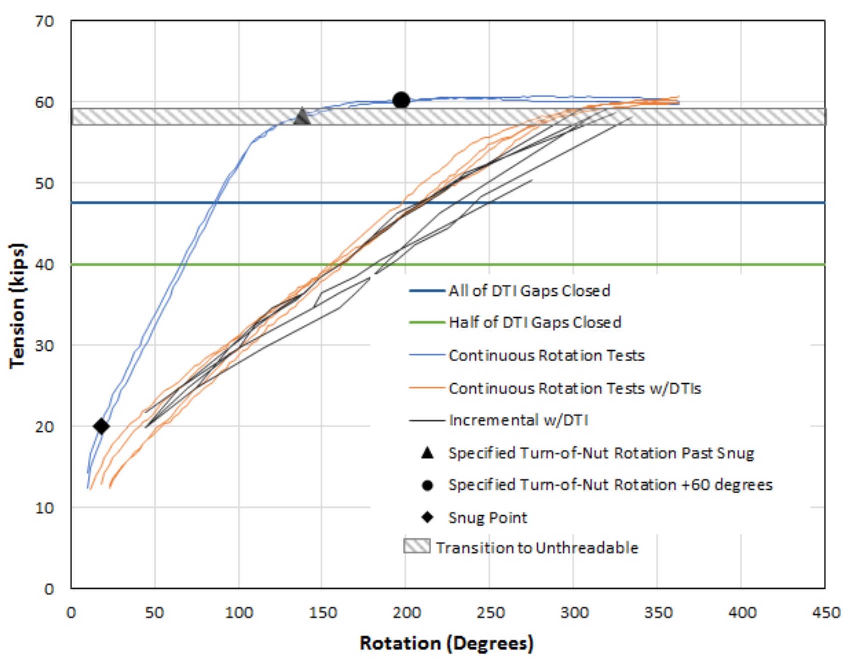

Figure 21. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 20 kips. 7/8-in. diameter, Bolt Manufacturer B, Grade A325 Type 3.

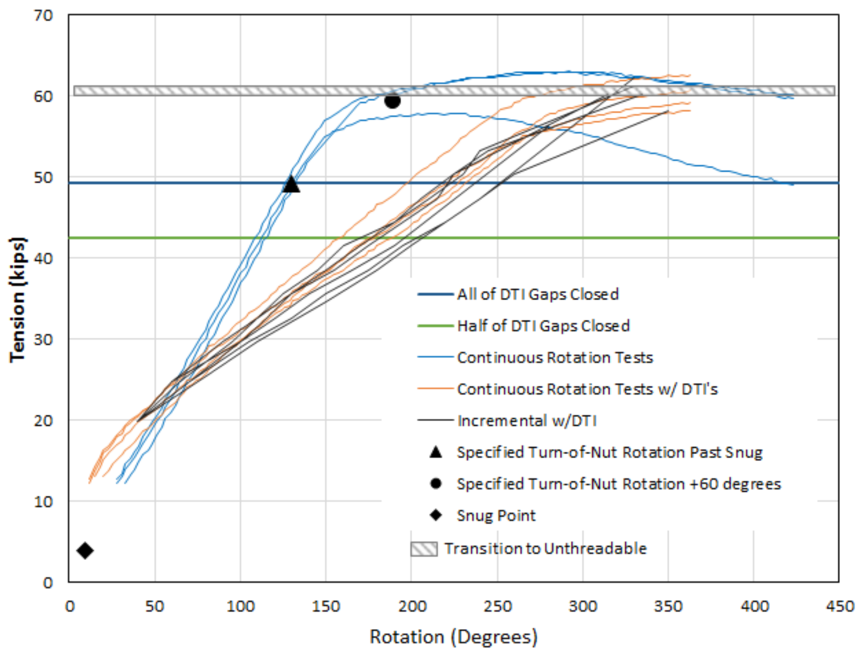

Figure 22. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 7/8-in. diameter, Bolt Manufacturer A, Grade A325-MG.

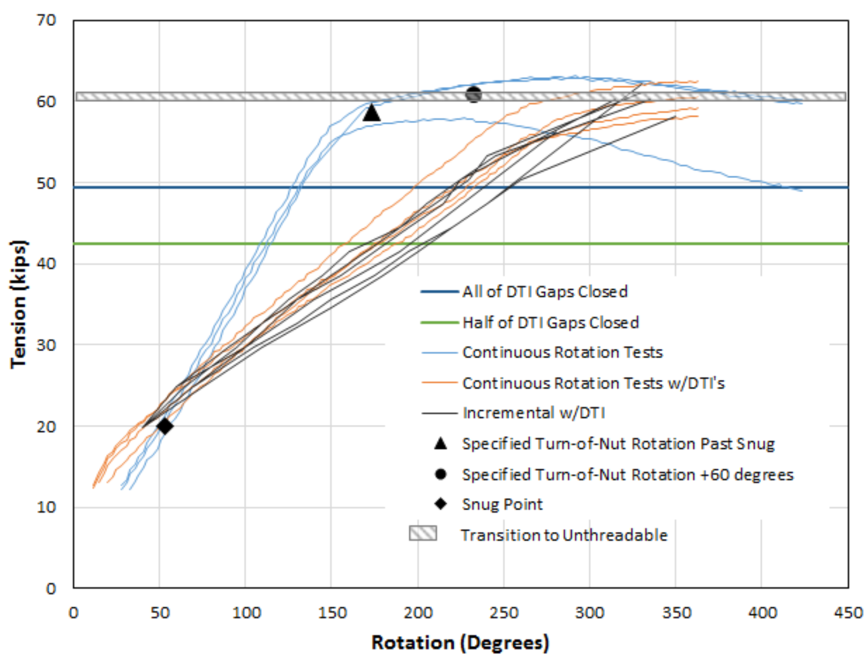

Figure 23. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 20 kips. 7/8-in. diameter, Bolt Manufacturer A, Grade A325-MG.

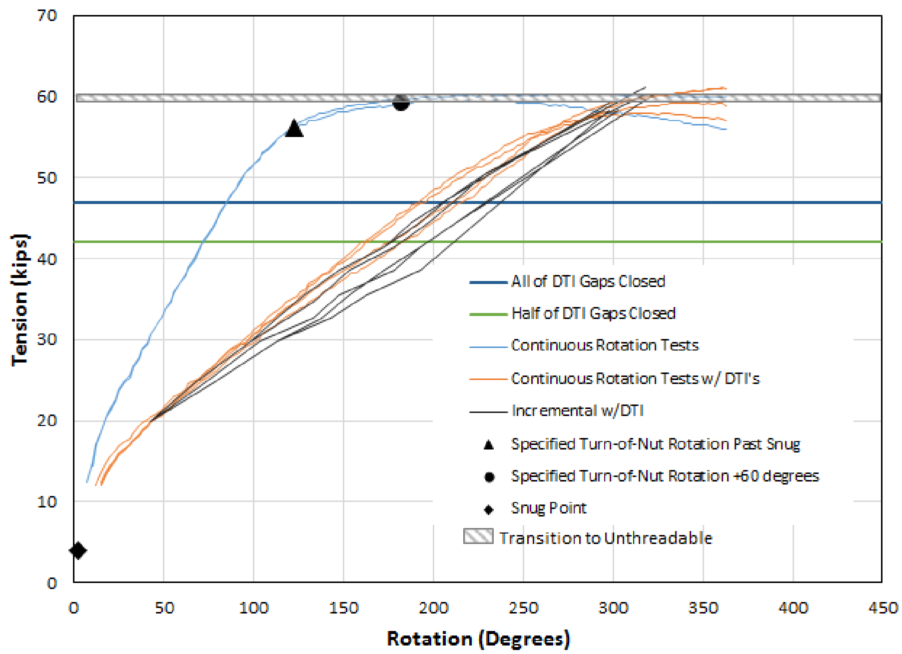

Figure 24. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 7/8-in. diameter, Bolt Manufacturer B, Grade A325-MG.

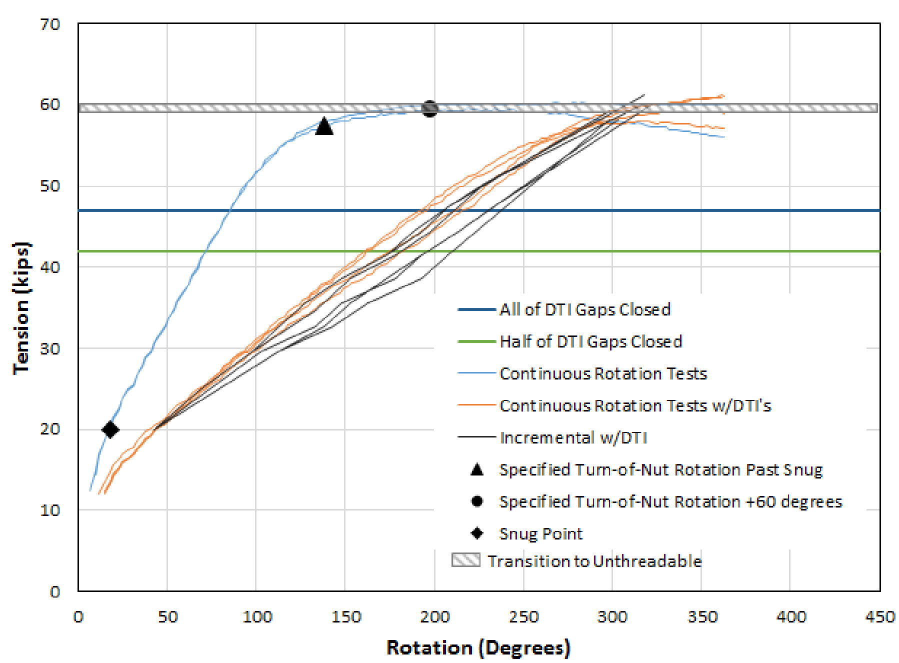

Figure 25. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 20 kips. 7/8-in. diameter, Bolt Manufacturer B, Grade A325-MG.

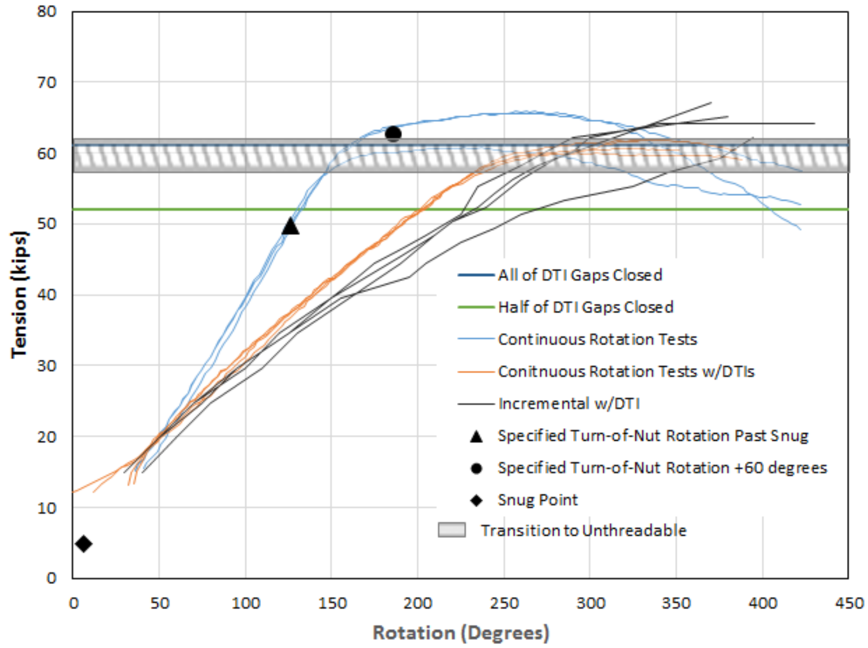

Figure 26. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 7/8-in. diameter, Bolt Manufacturer A, Grade A490-1.

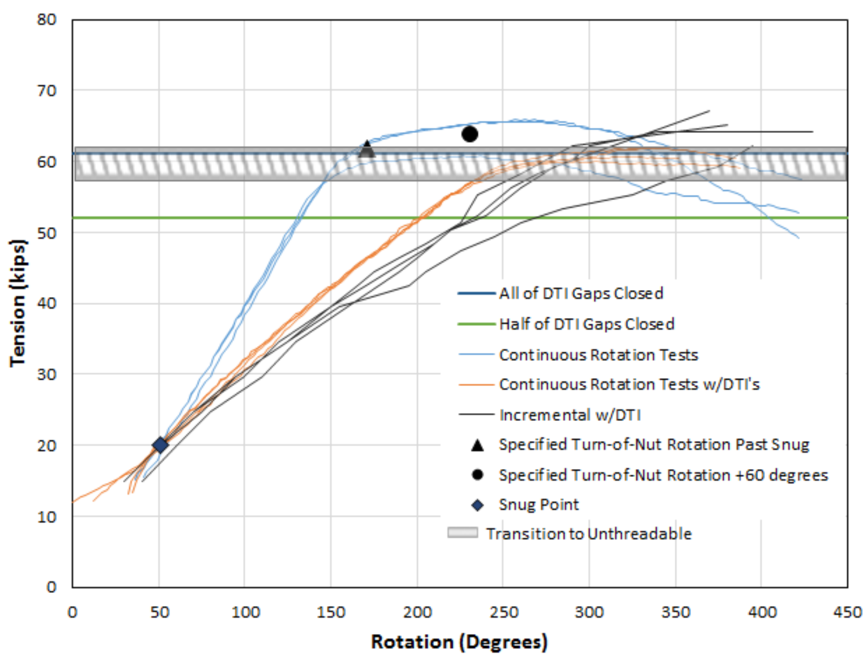

Figure 27. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 20 kips. 7/8-in. diameter, Bolt Manufacturer A, Grade A490-1.

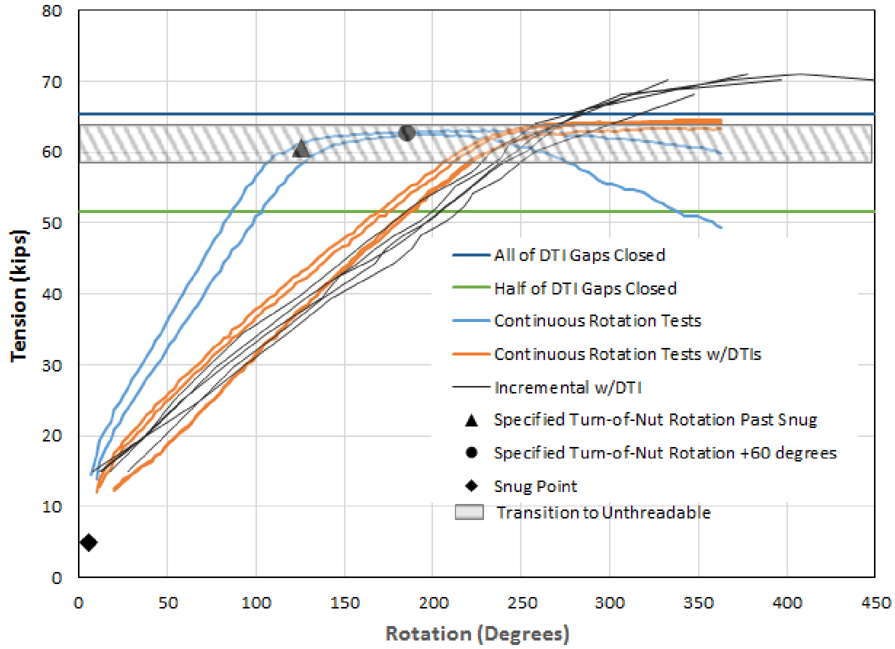

Figure 28. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 7/8-in. diameter, Bolt Manufacturer B, Grade A490-1.

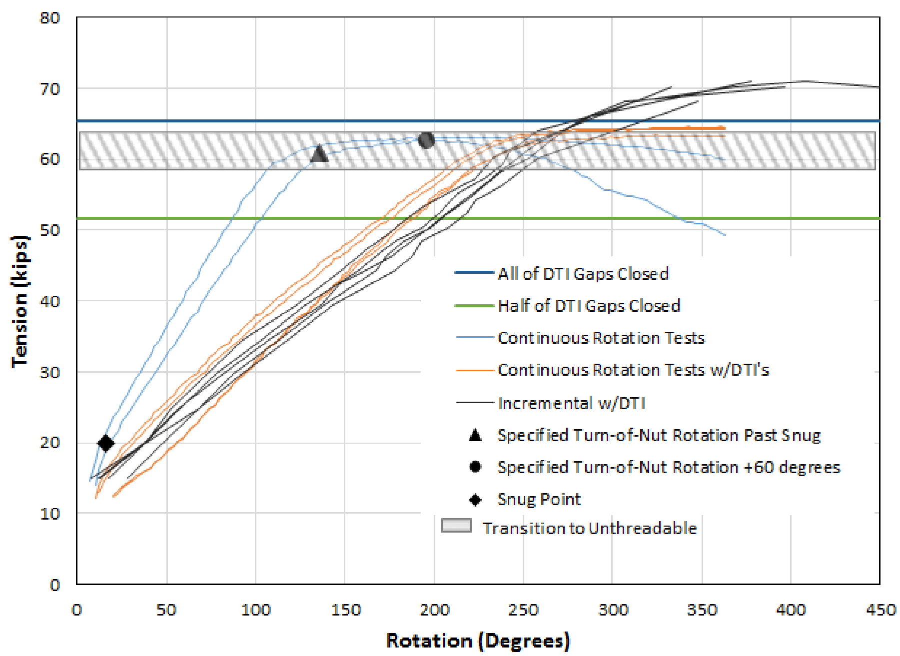

Figure 29. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 20 kips. 7/8-in. diameter, Bolt Manufacturer B, Grade A490-1.

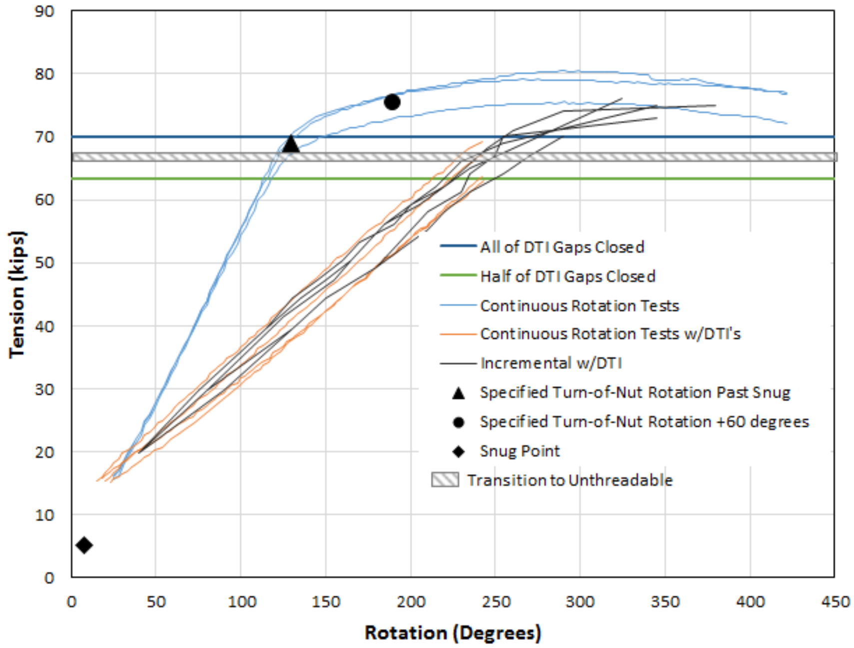

Figure 30. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 1-in. diameter, Bolt Manufacturer A, Grade A325-Type 1.

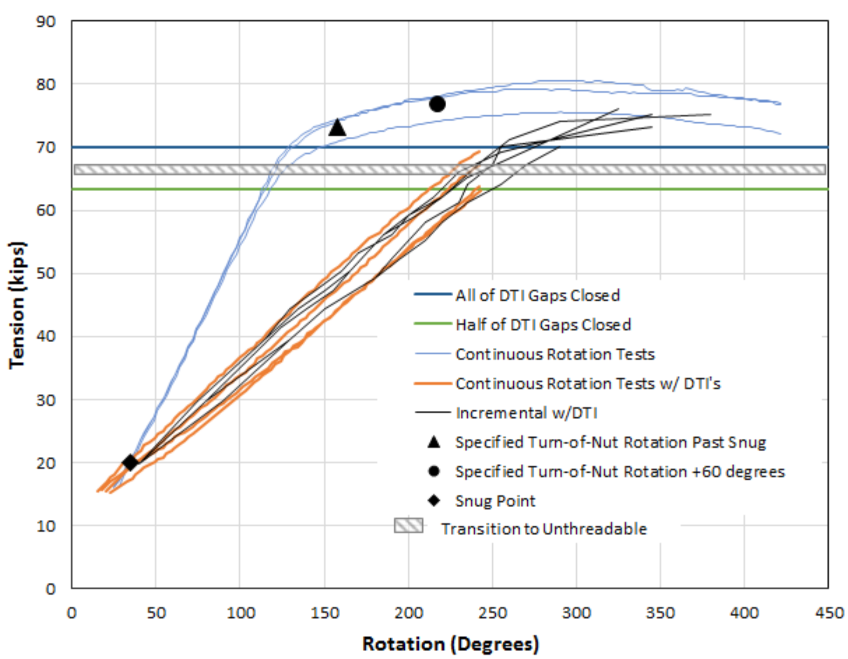

Figure 31. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 20 kips. 1-in. diameter, Bolt Manufacturer A, Grade A325-Type 1.

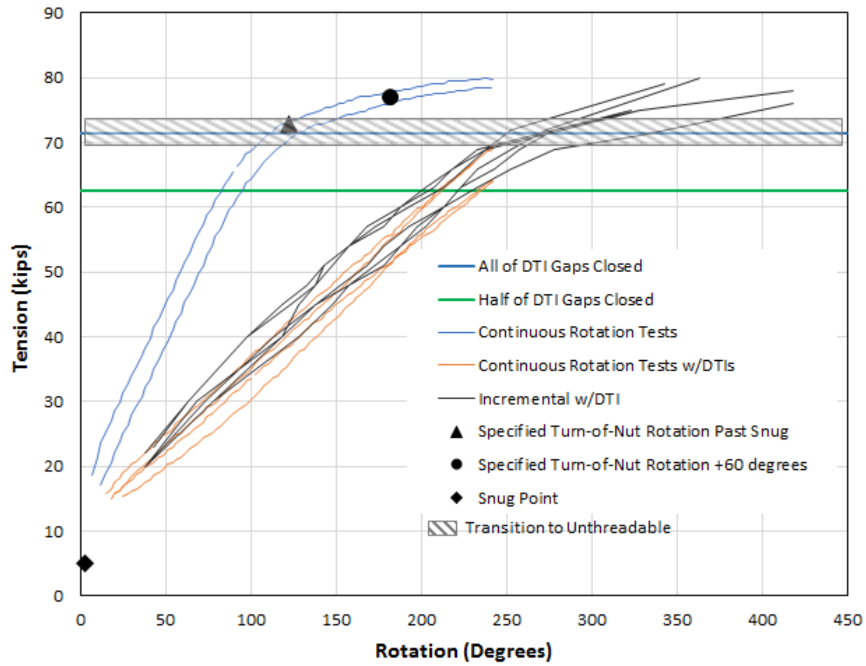

Figure 32. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 10% of minimum pretension. 1-in. diameter, Bolt Manufacturer B, Grade A325-Type 1.

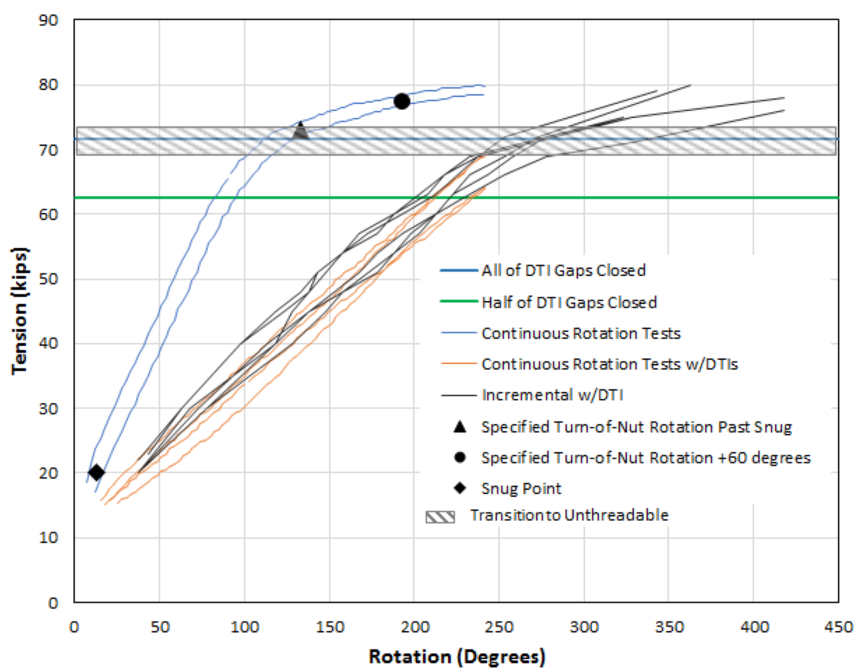

Figure 33. Comparison of Turn-of-Nut and DTI tensioning. Snug defined as 20 kips. 1-in. diameter, Bolt Manufacturer B, Grade A325-Type 1.

3.2 Rotation of the Nut 90^o Degrees Past the 'All-Closed' Condition

The AASHTO-stated installation and verification requirements for bolts installed using DTIs include prohibitions on full flattening of DTIs. However, a search of published literature does not reveal any evidence that flattened DTIs are associated with any reduction in performance. At least one paper published in the *AISC Engineering Journal* investigated the topic and reported rotations between 540^o to 720^o degrees with no detrimental effects from 'over-compressing' DTIs (Schmeckpeper, 1999).

Notwithstanding the lack of published work on the topic, AASHTO installation requirements for bolts with DTIs requires removal of any bolt, nut, and washer in which all DTI gaps have been compressed such that there is no visible gap. Similarly, in Europe, EN 1090-2 (Steel Structures) and EN 14399-9 (DTIs) previously had similar limitations without explanation, stating that no more than 10% of indicators within a connection should show full compression. More recently, these limitations have been removed from EN 1090-2, and EN 14399-9 allows all of the protrusions to be flattened.

The implications of a DTI with all of the gaps closed were further evaluated by considering an additional 90^0 rotation beyond the all-gaps-closed condition. In Figures 34 through 40, the measured average loads at which at least half and all gaps were closed in the incremental testing are superimposed onto the continuous load-rotation measurements performed on the 7/8-in. diameter assemblies. Data from incremental load tests are also included. A vertical line is then placed at an additional 90^0 rotation. An additional 90^0 rotation beyond the load at which all of the gaps closed placed the assembly still in upward sloping portion of the non-linear region. No bolt or thread failures occurred at a rotation 90^0 beyond the point the 0.005-in. feeler gage was refused in all openings. The implication is that, as currently calibrated, assemblies tensioned with the DTI method have significant reserve capacity to handle "over-compression" of the DTI.

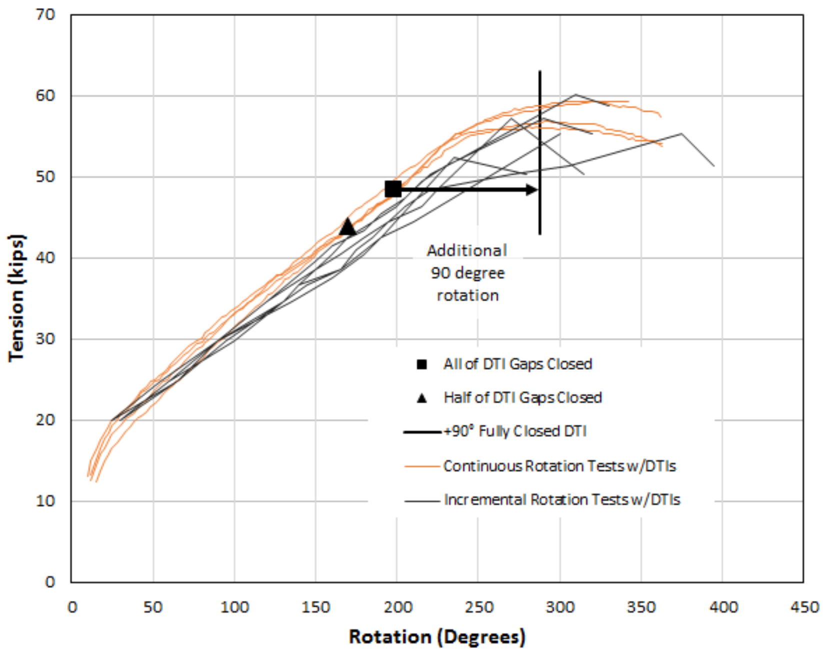

Figure 34. 7/8-in. diameter Manufacturer B, Grade A325 Type 1 bolt with DTI.

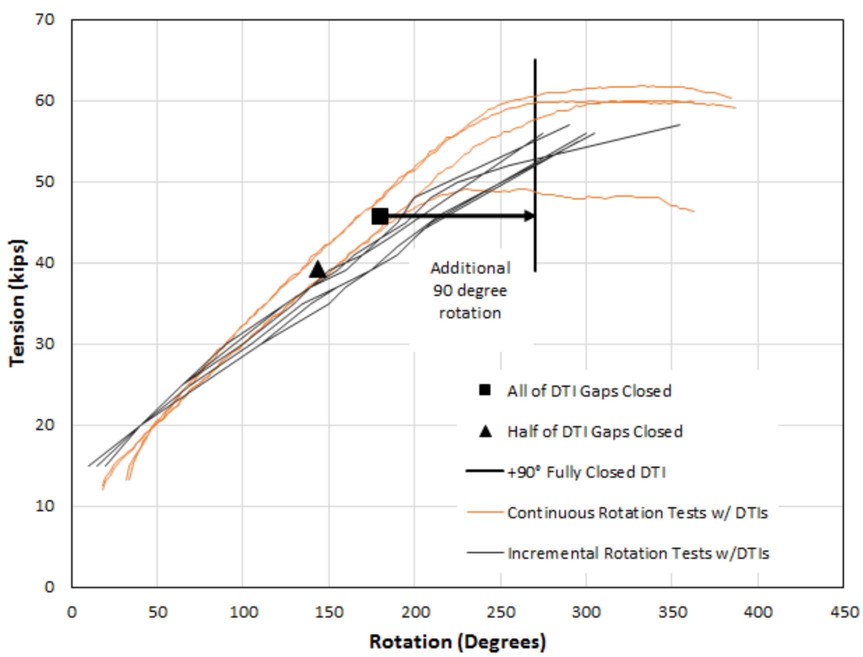

Figure 35. 7/8-in. diameter Manufacturer A, Grade A325 Type 3 bolt with DTI.

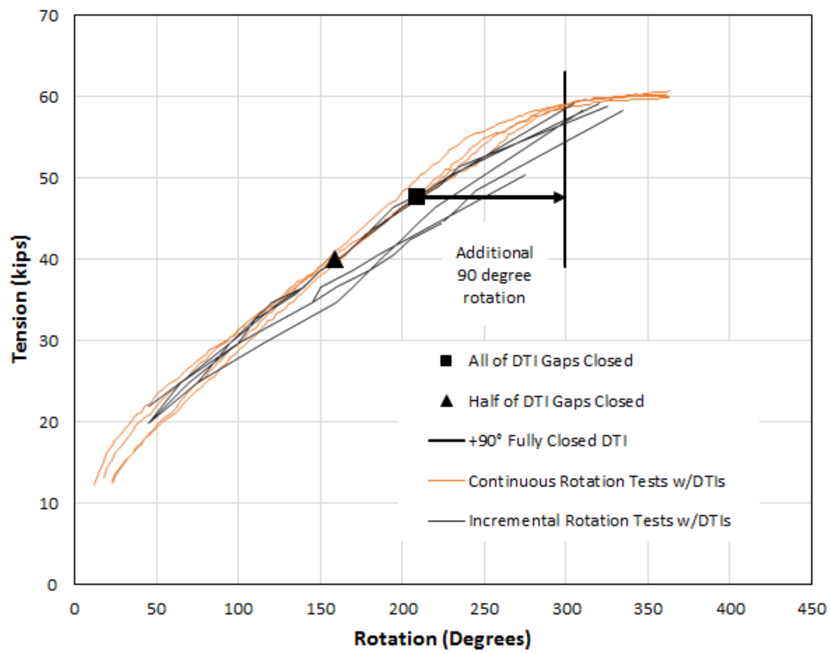

Figure 36. 7/8-in. diameter Manufacturer B, Grade A325 Type 3 bolt with DTI.

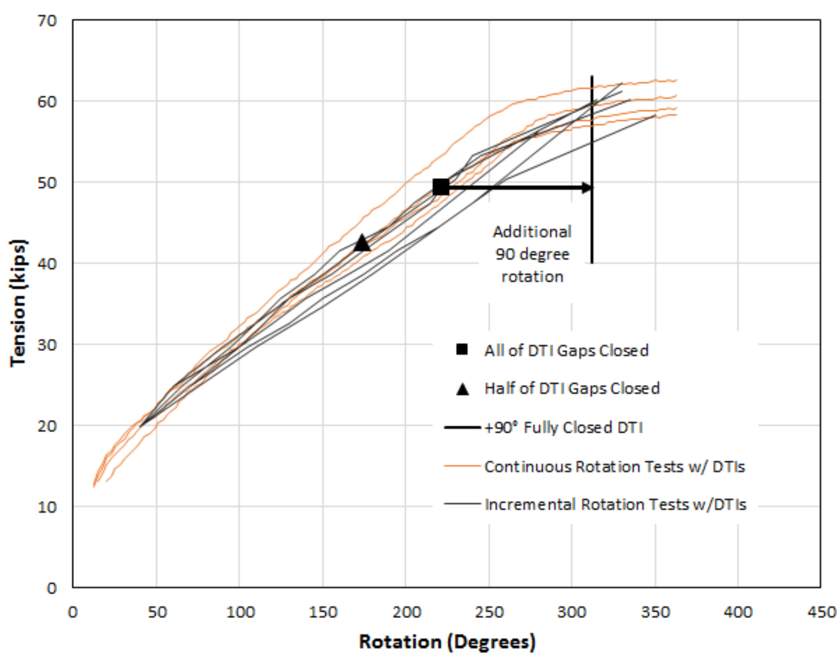

Figure 37. 7/8-in. diameter Manufacturer A, Grade A325 MG bolt with DTI.

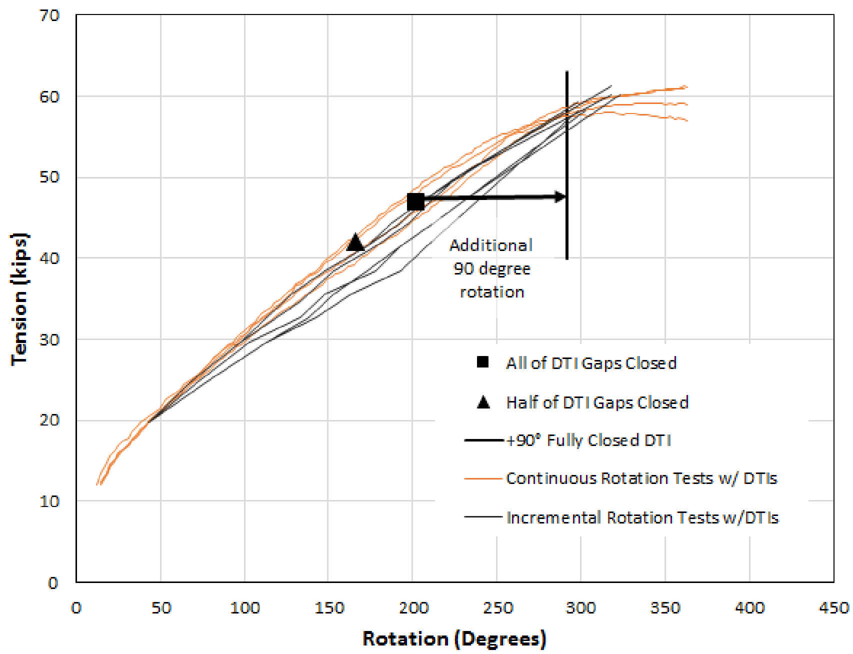

Figure 38. 7/8-in. diameter Manufacturer B, Grade A325 MG bolt with DTI.

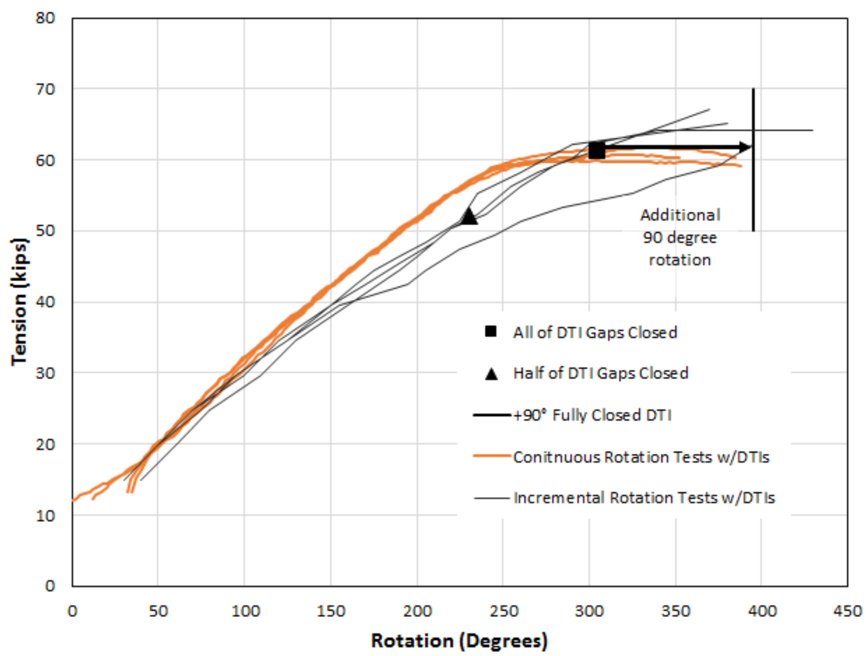

Figure 39. 7/8-in. diameter Manufacturer A, Grade A490-1 bolt with DTI.

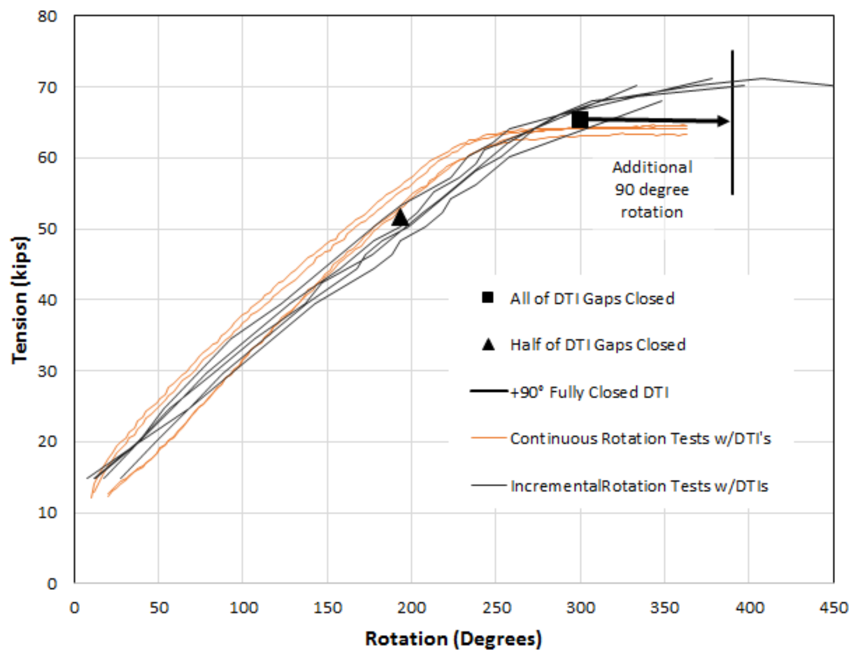

Figure 40. 7/8-in. diameter Manufacturer B, Grade A490-1 bolt with DTI.

4.0 Conclusions

The behavior of bolt assemblies tensioned using the Turn-of-Nut method and Direct Tension Indicator method to achieve a minimum pretension was compared. Multiple diameters and grades of bolts were used. In tests with the Turn-of-Nut method two starting "snug" conditions were considered for each diameter bolt. Testing of assemblies with DTIs focused on the bolt tension and deformation when at least half of the gaps and when all of the gaps were closed. For each bolt series the approximate load range in which permanent deformation of the bolt resulted in the inability to thread the nut the full length of the bolt was also determined. From this work the following conclusions were made:

- As was expected, more rotation of the nut is required for the same incremental increase in bolt tension when a DTI is used until all of the DTI gaps have been closed.
- In all of the cases studied, the Turn-of-Nut method with snug defined as 10% of the specified pretension resulted in a bolt tension above the required tension and usually within the linear range of the bolt behavior.
- When a more realistic snug condition was defined as 15 kips for 3/4-in. diameter bolts and 20 kips for 7/8-in. and 1.0-in. diameter bolts the resulting bolt tension achieved with Turn-of-Nut method was into the nonlinear region of the load-deformation behavior.

- Under the more realistic snug condition, the Turn-of-Nut method frequently resulted in a bolt tension that was at or above the range of loads determined to result in a condition in which the nut could not be run the full length of the threads.
- Assemblies with Direct Tension Indicators (DTIs) with half of the gaps closed always resulted in a bolt tension above the minimum required and lower than the tension produced by the Turn-of-Nut method – regardless of how the snug condition was defined.
- For the 3/4-in. diameter bolts, the load at which all of the DTI openings were closed was usually above the region identified as the transition to the nut no longer being capable being run the length of the bolt thread. However, this load was below the tension achieved using the Turn-of-Nut method from a realistic snug condition.
- For all of the 7/8-in., A325 tests the load at which all of the spaces were closed was well below the transition to the nut no longer being capable being run the length of the bolt thread and below the tension achieved using the Turn-of-Nut method from either snug condition.
- For the 1-in. diameter tests the load at which all of the spaces were closed was well above the transition to the nut no longer being capable being run the length of the bolt thread and approximately the same as or below the tension achieved using the Turn-of-Nut method from either snug condition.
- In the 7/8-in. diameter assemblies, an additional 90^0 rotation beyond the load at which all of the gaps closed placed the assemblies in upward sloping portion of the non-linear region.
- The lowest expected bolt tension produced using either the Turn-of-Nut method or the Direct-Tension-Indicator method are similar.
- The application of an additional 90^0 of rotation to a fully flattened DTI bolting assembly results in a condition similar to the Turn-of-Nut method utilizing a realistic snug point. Neither the Turn-of-Nut method utilizing a realistic snug point nor the Direct Tension Indicator method with completely flattened DTIs is correlated with bolt failures.
- The RCSC's statement for all four bolt installation methods that, 'a pretension that is greater than the value specified … shall not be cause for rejection' is consistent with the data.
- There were no significant differences in behavior of the assemblies using any combination of bolt and DTI from the two bolt and two DTI manufacturers.

The additional constraints on the DTIs method discussed above result in a much tighter band of allowed performance when a DTI is used compared to other tensioning methods. The current AASHTO verification testing requires that the nut must be able to run the full length of the thread after closure of all gaps results in calibration of DTIs such that the bolt remains in the linear region rather than in the more desired inelastic state. Modification of this AASHTO provision to be consistent with the Rotational Capacity Test provisions of ASTM F3125, that is require that nut only be able to be run to the position it was during the test, could result in calibration of DTIs to also produce the more desired inelastic condition. As currently written this is not achieved because very little inelastic deformation will prevent a nut from running the full length of the threads. While the AASHTO provisions are intended to prevent over-tightening during installation, the only practical limit on 'over-tightening' for any of the installation methods is bolt breakage.

5.0 Acknowledgements

This work was funded by TurnaSure LLC. TurnaSure LLC and Applied Bolting Technologies provided the DTIs used in the work. The bolts, nuts, and washers were provided by Haydon Bolts, Inc. Haydon Bolts, Inc. also provided the facilities and test equipment used for the continuous rotation testing. All findings and opinions expressed are exclusively those of the authors.

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