TESTS ON THE INSTALLATION CHARACTERISTICS OF HIGH STRENGTH FASTENERS IN LAP SPLICE JOINTS

by

MICHAEL CHRISTOPHER WEHR, B.S.C.E.

THESIS

Presented to the Faculty of the Graduate School

of The University of Texas at Austin

in Partial Fulfillment

of the Requirements

of the Degree of

Master of Science in Engineering

The University of Texas at Austin

May, 1995

TESTS ON THE INSTALLATION CHARACTERISTICS OF HIGH STRENGTH FASTENERS IN LAP SPLICE JOINTS

APPROVED BY THE

SUPERVISING COMMITTEE:

_____

Michael D. Engelhardt

_____

Karl H. Frank

This thesis is dedicated to my partner for life

Deborah Dianne Kalisz Wehr

“one war, two children, three moves, and anything in the future...”

ACKNOWLEDGMENTS

I should begin by thanking my sponsor, the US Army, but that's a bit too impersonal. The individual paratroopers who were willing to follow me and kept me motivated get the first thanks. I would not be here if it were not for them.

Once here, there are many people who helped me make it to this day of writing a note of thanks. Dr. Michael Engelhardt, my advisor convinced me that I had a chance to make it through the curriculum even though I could not tell him the difference between LRFD and ASD when he asked me what I had studied 10 years ago. You have my sincere appreciation for instilling confidence. Dr. Frank was the first professor I met and the last signature on this thesis. Thank you for your insights on my true interest in steel structures.

I am indebted to Darin Riggleman for his patience in assisting me in getting started on the research for this thesis.

The staff of Ferguson laboratory provided everything a new research assistant needed to survive. Wayne Fontenot, Wayne Little and Pat Ball helped me get oriented with all the equipment I used. Ryan Green and Ray Madonna were critical due to my slow but eventual understanding of electronic equipment. Blake Stasney kept me on track with just the strange looks he would give me if I was trying something I shouldn't. I was always impressed with the way everyone was willing to answer the numerous and redundant questions of all students. A special thanks goes out to Laurie Golding, the expert in logistics. Every officer in the Army would be lost without someone to keep the supplies on line. Thanks again. Beth Miller, thank you for your dedication to helping any student in need of assistance.

I would like to point out my gradatude towards Ranjit Gupta and Mike Gilroy. Without them I would be here another semester still drilling bolts. Actually, their friendship and patience is as valued as all their long hours of work.

As with any challenging experience, there are a few people I have been lucky enough to share the struggle with. I am truly indebted to them for making my short time in graduate school very rewarding. Jeff Schmitz has been invaluable as a friend and source of motivation. Sarah, Valerie, and Reagan have been true inspirations for achievement. With the help of Dr. Bollinger and Eric Soderberg I have avoided many possible set-backs. I

want to thank Chad Corsten for his help and inspiration to stay up all those nights to finish this thesis. Mike Smart was a great inspiration for working hard from the very beginning. Thanks Vince for all the late night discussions on life and engineering in general. Best of luck to you. Also, Kevin Moore enjoy the city by the bay, I'll be there someday. A special thanks to Willie Ramirez and Robert Frosch for their friendship and photographic assistance. Also, Rob Zorbel and Brad Wood, best of luck to you both. Joe Muscarella, thanks for your friendship and mentorship, best of luck at West Point.

It is important for me to remember the people who are responsible from the beginning for any success I enjoy. My parents and brothers and sisters are a constant source of inspiration and love. Thank you.

As always, I have tried to thank everyone, yet without mention of my family. My wife, Deborah and children, Rachel and baby Chuck, have helped me the most in getting me through school, as with any challenge in my life. You have my heart.

Michael C. Wehr
December, 1994

ABSTRACT

TESTS ON THE INSTALLATION CHARACTERISTICS OF HIGH STRENGTH FASTENERS IN LAP SPLICE JOINTS

by

MICHAEL CHRISTOPHER WEHR, M.S.E.

The University of Texas at Austin, 1995

SUPERVISOR: Dr. Michael D. Engelhardt

The proper performance of slip-critical bolted joints requires adequate fastener tensions. The Research Council on Structural Connections of the Engineering Foundation requires minimum fastener tensions for these slip-critical connections. Past research done in the field and laboratory indicates variations in final fastener tension. Different methods of tightening fasteners and different conditions of the joined materials result in various final fastener tensions.

This thesis describes the research of various methods of tightening fasteners by conducting experiments on joints with instrumented fasteners. Electronic strain gauges provide information that translates into real time fastener tension. The turn-of-nut and calibrated wrench installation methods provide the main delineation between tests. Both of these methods of installation rely upon a "snug tight" condition before application of a final tightening pass. Tests conducted provide information on the adequacy of different "snug tight" conditions. Also, variations in connected material thickness and out-of-flatness affects final fastener tensions. Twenty-nine tests evaluate the results of using different combinations of tightening and material conditions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. CHAPTER 1
INTRODUCTION

1.1 GENERAL

This thesis describes the methods and results of various tests performed to measure fastener tension in a structural steel lap splice with deformed plates. Fastener tension is critical to the performance of a steel slip-critical connection. Slip-critical connections transmit applied loads using the frictional forces between connected surfaces. Fastener tension induces the frictional forces within the connection.

This research reflects an effort to evaluate fastener installation provisions in the "Specification for Structural Joints Using ASTM A325 or A490 Bolts"[1], by the Research Council on Structural Connections. This publication is referred to as the *Bolt Specification*. The standards for joint assembly and tightening of slip-critical connections were investigated. Twenty-five of the twenty-nine connection tests conducted in this study used either turn-of-nut tightening or calibrated wrench tightening on conventional 7/8 inch A325 galvanized fasteners. The last four tests, using the lock-pin and collar fastener, evaluated the installation method of alternative design bolts. The lock-pin and collar fasteners used in this study were manufactured by Huck International Inc, and will be referred to as Huck fasteners in this study.

Four primary factors that affect fastener tension are the method of installation, the sequence of tightening, the thickness and out-of-flat condition of the connected material, and the degree of "snug tight" existing between the material before final tightening. The *Bolt Specification* provides for four methods of fastener installation. The turn-of-nut and calibrated wrench methods of installation provided a basis for fastener tension comparison throughout this research. Each method of installation incorporated three different sequences of tightening. One sequence followed the path of tightening fasteners from the middle of the connection to the outside edges, as recommended in the *Bolt Specification*. Another sequence involved tightening fasteners from one side of the connection to the other side. Finally, the third sequence tightened fasteners on the outside of the connection followed by tightening the middle fasteners. All tests used one of three connection thicknesses. All

connection tests used deformed plates. Specifically, the contour of the interior plate in the lap splice was bent in single curvature to create a 3mm or 6mm gap. The two exterior plates were flat. Three different snug tight conditions attempted to bring the deformed plates into firm contact prior to final fastener tightening.

The study reported herein is continuation and extension of a similar study by Riggleman (1994). The reader is referred to Riggleman's thesis for further background on this study.

1.2 CURRENT METHODS OF FASTENER INSTALLATION

The *Bolt Specification* describes four methods of fastener installation for the assembly of slip-critical connections. All methods must achieve at least the tension identified as 70% of the minimum tensile strength of the fastener. For A325 bolts with a diameter of 7/8", the required minimum tension is 39 kips. Tightening may be done by turning the bolt or the nut, provided one is held against rotation. The two methods of installation evaluated in this research are the turn-of-nut and calibrated wrench methods.

The turn-of-nut method relies on a specified rotation of the nut to achieve a minimum of 39 kips of tension. This turn-of-nut occurs after the plies of the material in the connection are in firm contact. The *Bolt Specification* requires that a sample of three fastener assemblies are tested in a device capable of measuring bolt tension. The tested samples must achieve a tension not less than 41 kips, (5% greater than the minimum of 39 kips). The method of estimating the snug tight condition (when the plies are in firm contact) must be verified. When snugging the plies together and when applying the turn-of-nut, the sequence of fastener tightening should progress from the most rigid part of the connection to the free edges. More than one snugging pass may be required to achieve the snug tight condition. After achieving the snug tight condition, the amount of nut rotation depends on the bolt length. For the length of fasteners used in this research, the rotation was either 1/3 or 1/2 of a turn.

The calibrated wrench method must achieve the same 41 kips of tension when evaluated with three sample fasteners in a tension measuring device. The method must not produce a rotation of the nut beyond what is required of the turn-of-nut method. A hardened washer is required under the element being turned. The wrench must be calibrated at least

daily and if there is a change in the condition of the equipment or fasteners. The actual tightening pass with a calibrated wrench occurs after the plies of the connection are in the snug tight condition. The sequence follows the same path of moving from the most rigid portion of the connection to the free edges. More than a single pass of tightening may be required.

1.3 SUMMARY OF PREVIOUS RESEARCH

The four primary factors affecting final fastener tensions have been addressed to some degree in various publications. The literature search revealed two studies that focused on field conditions and one study based mainly in the laboratory. The *Bolt Specification* [1] and another design criteria publication make up the total of five publications with information pertinent to this report.

The turn-of-nut and calibrated wrench methods of installation are directly compared in the tests conducted in this report. Section 1.2 addressed the specifics of the two methods as indicated in the *Bolt Specification.* Kulak, Fisher, and Struik [2] mention that the turn-of-nut method achieves higher fastener tensions. This appears to be true if the process of installation follows the *Bolt Specification* guidance of achieving firm contact between plates before the final turn-of-nut. However, both field studies reviewed in the literature search reveal the challenges of implementing the turn-of-nut method of installation. Kulak and Obaia [3] documented the findings observed during the construction of three bridges. 7/8" diameter A325 fasteners were installed using the turn-of-nut method. The bolting crews did not follow the requirements of the *Bolt Specification* completely. Using an impact wrench, fasteners were often completely tightened without a snugging pass to bring connected materials together. Also, the actual rotation of the nut was not monitored closely. Based on the sound of the impact wrench, a fastener was determined to be tight. However, despite this, almost all fasteners were at the required minimum tensions upon inspection. The critical observation at the end of this particular publication is that this result would not have been obtained had the connected materials been deformed.

Notch [4] further exposes the problems with the turn-of-nut method encountered in the field. Testing and observations focused on the installation of 1" diameter A490 fasteners in oversized holes. In the process of investigating the effects of not having the proper

hardened washers, many fasteners were found to have below minimum tensions. Observations indicated similar discontinuities in keeping track of the rotation of the nut. Also, bolt crews often did not apply a snugging pass before the complete tightening of a fastener.

Notch [4] makes an important point when comparing the turn-of-nut method and the calibrated wrench method. While there were problems in the past with the calibrated wrench method achieving dependable results, the turn-of-nut method has a potentially more serious short fall. The turn-of-nut method is not effective unless a snug tight condition is achieved first. This is demonstrated in some of the tests of this report. As will be discussed, defining this snug tight condition may be more difficult than ensuring accurate calibrated wrench tensions. Notch proposes a more stringent calibrated wrench method.

Foreman and Rumpf [5] did a series of tests with A325 bolts to validate the capacities of bolted connections. The focus of their research was to prove the overly conservative nature of replacing rivets with bolts, one for one. Almost as a side note, mention was made of the need to touch-up fasteners with an additional turn-of-nut after the first turn-of-nut pass. The method of determination involved the operator of the impact wrench checking the tightness by the sound of the impact wrench. Very few fasteners required additional rotation of the nut. However, the requirement of applying only one turn-of-nut pass, as indicated in the *Bolt Specification*, precludes an operator from doing this check. This offers some credence to the suggestion of Notch for a more stringent calibrated wrench method.

The *Bolt Specification* requires that the snugging and tightening sequence must progress from the most rigid part of the connection to the free edges. The field studies of Kulak and Obaia [3] and Notch [4] indicate that this does not necessarily happen. Both studies focus on other factors that were considered more critical in achieving the minimum tensions. Therefore, one aspect of this current research is to investigate the differences between tightening sequences.

Observations by Birkemoe [6] on the effects of out-of-flat plates within the connection are of significant interest in regard to the research conducted for this report. The publication produces evidence of low fastener tensions due to out-of-flat plates. The connections tested are similar to those used throughout this report. Connections of the

publication consisted of single or triple curvature interior plates between two exterior flat plates. The intent was to simulate the plate distortion that might occur due to welding, handling, or erection. During the snugging pass and the tightening pass, fasteners were found to loose significant amounts of tension. Normally, the fasteners first tightened lost the most tension. Birkemoe also comments on the need for multiple snug passes to achieve the snug tight condition called for in the *Bolt Specification*.

Notch [4] identifies the reliance the turn-of-nut method places on the snug tight condition. The rotation of the nut required to achieve the minimum tensions is not clearly apparent if the turn-of-nut is doing the job of a snugging pass. The *Bolt Specification* indicates the need for the snug tight condition, however, Notch points out that the definition of snug tight is "elusive".

1.4 OBJECTIVES OF RESEARCH

The proper performance of slip-critical bolted connections requires adequate fastener tensions. Different methods of tightening fasteners within a connection result in various final fastener tensions. The primary objective of this report is to evaluate the final fastener tensions for each method of tightening. The two secondary objectives are to validate the method of measuring fastener tensions and to describe the various degrees of snug tight for each connection test. With the descriptions of snug tight and the results of the tests, some correlation can be made to define the abstract definition of the snug tight condition in the *Bolt Specification.* This research evaluates the effects of the installation method, the tightening sequence, the connection thickness / deformation, and the snug tight condition.

1.5 OVERVIEW OF RESEARCH CONDUCTED

Three phases of research constitute the formulation of this report. They are outlined below:

Phase I: Review of literature.

Phase II: Behavior of the strain gauge in measuring fastener tension.

Phase III: Examination of fastener tensions in connection tests.

The literature review of Phase I was detailed in Section 1.3 of this chapter. Phase II consisted of a series of tests to verify the value of tension indicated by the strain gauge inside a fastener. Specifically, the effects of bending, torsion, and fastener yielding were investigated. Phase III constituted the majority of the research. Twenty-nine connection tests provided detailed information on the various combinations of the installation method, sequence of tightening, plate thickness / deformation, and the degree of the snug tight condition.

1.6 ORGANIZATION OF REPORT

Four chapters are dedicated to documenting Phases II and III mentioned in Section 1.5. Chapter 2 describes the type of connection used for all tests. A description of measuring plate out-of-flatness and the snug tight condition for all tests is the primary purpose of Chapter 2. Chapter 3 documents the behavior to the strain gauge used to measure bolt tension. The effects of torsion, bending, and yielding are all investigated in Chapter 3. Chapter 4 and Chapter 5 summarize the fastener tensions for conventional fastener tests and lock-pin and collar fastener tests, respectively. For each test, these two chapters describe the specific combination of the four primary factors that affect fastener tension. These factors are the installation method, the tightening sequence, the plate thickness / deformation, and the snug tight condition. Chapter 6 presents the summary and conclusions of this research.

2. CHAPTER 2
MEASURING OF PLATE DEFORMATION

2.1 GENERAL

A connection test consisted of 12 fasteners installed in a three plate lap splice. The splice was made up of a thick interior plate with thinner plates on the exterior. Specifically, the middle plate was twice the thickness of an exterior plate. All tests involved the same

plates used by Riggleman (1994). The summation of all plate thicknesses within a connection is the grip length of that connection. Grip length refers to the length of fastener that exists within a connection. Connection tests evaluated three grip lengths of 2", 3", and 4". Figure 2.1 shows the plates for all three grip lengths. All plates were 12" by 12" in plan view. Table 2.1 is a summary of plate thicknesses for each grip length . Figure 2.2 is a photo of the lap splice in the test set-up. Figure 2.3 shows the dimensions of the lap slice.

Grip Length (inches)	Thickness of Interior Plate (inches)	Thickness of Exterior Plates (inches)
2	1	1/2
3	1-1/2	3/4
4	2	1

Table 2.1: Plate Thicknesses for Three Grip Lengths

Out-of-flat plates present a significant challenge for fasteners in a slip-critical connection. All tests involved an out-of-flat interior plate. The exterior plates were flat. The gap created between the middle plate and the exterior plate was either 3mm or 6mm at the beginning of each test. The intent of tightening the fasteners was to eliminate this gap and achieve the required final tension in the fasteners.

Figure 2.1: All plates used for the three double shear lap splices

Figure 2.2: Lap splice in test set-up

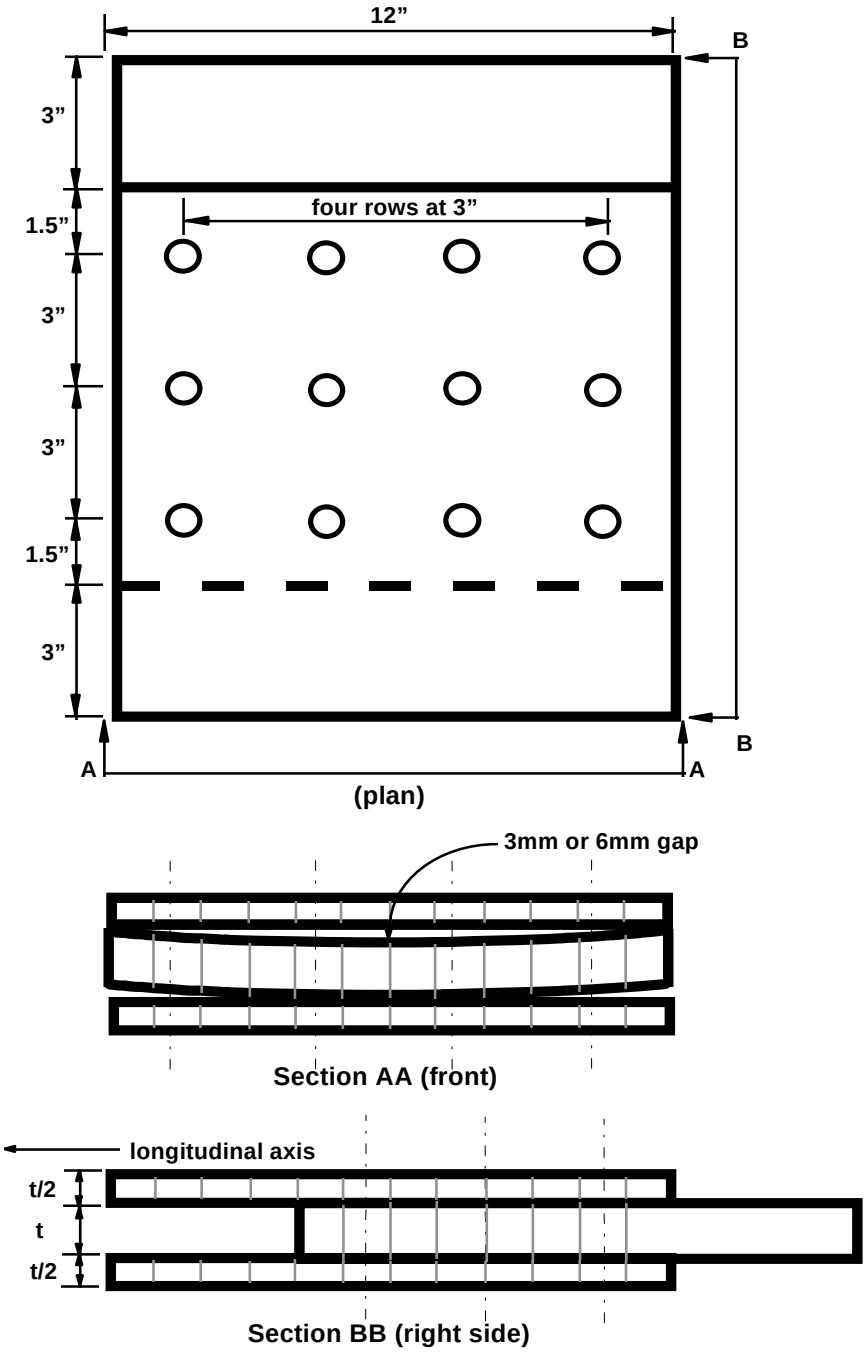


Figure 2.3: **Dimensions of lap splice**

It should be noted that the three grip lengths correspond to the three bent plate thicknesses. Two grip lengths of equal total thickness, but with different thickness middle plates will not produce the same test results. The intent of the three grip lengths is to demonstrate the outcome of using three different thicknesses of bent plates. More force is necessary to close the gap of a thicker bent interior plate.

This chapter describes the condition of the plates throughout the testing as well as the preparation (Section 2.2) and measurement (Section 2.3) of each plate. Before every test, each plate was measured and "shaped" as necessary through plastic bending. Exterior plates were flattened to within 0.01". Middle plates were bent to the required gap of 3mm (0.118") or 6mm (0.236"). All tests involved two methods of measuring the gap created by the shape of the plates. The information from these two measuring methods is presented for each test in Section 2.5. Plots in Appendix A graphically shows the change in gap around the perimeter of the connection, after the snugging and tightening passes.

2.2 METHOD OF BENDING PLATES

In preparation for every test, exterior plates had to be made flat and interior plates had to be bent to the required gap. Cold bending changed the shape of the plates. To bend a plate, two bars supported the edges of the plate while a load was applied along the span between the supports. A 600 kip test machine applied the load necessary for bending as pictured in Figure 2.4 and Figure 2.5. The supports and applied load were along the entire length of the plate. The single curvature induced (or removed for flat plates) was opposite in direction to the applied loading. This curvature is about the longitudinal axis of the lap splice.

The initial gap measured between the middle plate and the top plate was 3mm for 21 tests and 6mm for 8 tests. Two of the four figures for each test in Appendix A graphically show the shape of this curve for the front and back edges of the middle plate. Depending on the locations of the holes, the front or back edge curves varied slightly from each other. A flat bar resting on top of the plate provided a reference to measure the curvature and flatness of the plate. Calipers measured the gap between the flat bar and the plate. This process is described in Section 2.3.

Figure 2.4: Bars used for plate bending

Figure 2.5: 600 kip Satec test machine bending plate

2.3 DEFORMATION MEASUREMENTS BEFORE AND AFTER TESTS

The first method of gap measurement consisted of recording the bend that existed in each plate before it was placed in the connection. This bend is described as the curve that exists in a plate when looking at its front view. Relative to the alignment of the plate in the connection, this curve is about the longitudinal axis of the splice connection. Eleven locations at 1" intervals along the sides of each plate identify the gap measurement locations. These eleven locations are seen in Figure 2.3, along the edges of the front and right side views.

The front and back edges of each plate were measured for curvature. The left and right edges remained fairly flat throughout all testing. Therefore, no initial measurements were taken along these edges until the plates were in the connection test. Before each test, a single flat bar (1/2"x15"x2") provided a reference for all front and back edge deformation measurements. As seen in Figure 2.6, the flat bar created a gap between itself and the curved surface of a plate. Calipers measured the total thickness of the flat bar, the plate, and any gap that existed between the two, as seen in Figure 2.7. Subtracting the known thicknesses of the bar and the plate from each of these measurements produced the gap depth. Applying a load as described in Section 2.4 shaped the plate to the necessary flatness or curvature. The gap depth was measured both before and after each test. The gap depth measured before the test provided the data for the "no load" gap for the figures of Appendix A. The gap depth measurements described in the next section provided the data for the "snug" gap, the "tight" gap and the "touch-up" gap for the figures of Appendix A.

2.4 DURING TEST MEASUREMENTS

The measurement of the gap between plates during a connection test was a challenge. Ideally, the gap that existed between plates throughout the connection could be directly obtained. The particular gaps of interest would be the gap after a snug pass and the gap after a tightening or touch-up pass. However, a method to "get inside the connection" to measure the gap was beyond the scope of this research. The method actually used

Figure 2.6: Flat reference bar on plate

Figure 2.7: Calipers measuring the total thickness of flat bar, plate, and gap

obtained gap information around the perimeter of the connection with the use of a feeler gauge.Figure 2.8 shows the method of using the feeler gauge. The previous method of using a flat bar and calipers would not fit on the plates when they were in the connection support

frame. A feeler gauge measured the gaps that existed between the plates while in the connection. The gaps were measured after the snug, tight, and touch-up pass. Two levels of gap were measured, specifically, the gap between the middle and top plate and the gap between the middle and bottom plate. Data was taken around the entire perimeter of the connection. As mentioned previously, the edges of the plates were marked at 1" increments. These markings provided the locations of gap measurement with the feeler gauge. Eleven locations were measured on the front and back of the connection, while eight locations were measured on the left and right sides of the connection. Figure 2.3 shows the locations of measurement. The feeler gauge measured the depth of the gap to within 0.005" increments.

It should be noted that the gap was not measured with a feeler gauge before the snug pass. Information from the flat bar measuring method provided this initial "no load" gap data. The closing of the gap for each test is described in Section 2.5. Information from both methods of gap measurement create the curves presented in Appendix A.

2.5 GAP HISTORIES FOR TESTS

Using the gap information described above, four figures (Appendix A) for each test present the change in gap between plates during a test. The test designations, such as "CD2TN123.MTO" are defined in Chapter 4. While data was obtained for eight gaps in each connection (four sides for both the interior / top plates and interior / bottom plates) only the gaps of interest are presented. The front and back gaps between the interior and top plate are presented first. Then the left and right side gaps between the interior and bottom plates is presented. All data is plotted in reference to the location along the 1" increments of the exterior plates. The eight points of measurement for the side gaps represent the overlap in the lap slice of the interior and exterior plates. Each figure plots the gap at the edge of the plates. Up to four lines exist on each plot. The orientation of the plots is just as the plates would be viewed while in the connection support frame. The lines represent the edge of the lower plate creating a gap with the upper plate. In other words, for the first two figures of each test the plotted lines are the edge of the interior plate while the top x-axis represents the edge of the top flat plate. For the second two figures, the plotted lines represent the bottom plate with respect to the edge of the middle plate. The edge of the middle plate shown as the top x-axis is physically above the bottom plate due to the initial curve of the middle plate.

The four lines plotted indicate no-load, snug, tight , and touch-up conditions. 12 of the 29 tests have touch-up passes. It should be noted that if a snug, tight, or touch-up line is mentioned in the figure's legend, but is not visible on a plot, the gap is closed. The first test CD3TN122. MTO does not have gap information.

Figure 2.8: During test gap measurements with feeler gage

3. CHAPTER 3
BEHAVIOR OF THE BTM STRAIN GAUGE

3.1 GENERAL

All fasteners used in this study were instrumented with a special strain gauge specifically intended for use in bolts. This gauge is produced by TML, a Japanese strain

gauge manufacturer. This gauge is designated as type BTM-6C by TML, and will be referred to simply as the BTM strain gauge in this report. The BTM gauge is installed in a 2mm diameter hole drilled through the head of the fastener, and is located along the longitudinal axis of the fastener, in the upper unthreaded portion of the fastener. All tested fasteners employed the method of gauge installation developed by Riggleman (1994). The Sheldon 10" horizontal lathe used for drilling the 2mm diameter hole in the fasteners is pictured in Figure 3.1. Also, all the materials and tools used for installing the gauge in the 2mm hole are pictured in Figure 3.2. These are the same materials specified by Riggleman (1994).

Understanding the performance limits of the BTM strain gauge is essential to research study. The calculation of bolt tension required an accurate method of converting recorded strain (micro in/in) to a fastener tensile load measured in kips. Unique to each fastener, a calibration factor converted strain to tensile load. Various tests with conventional fasteners evaluated the accuracy of this calibration factor, as discussed in Section 3.2.

Fastener tension is the primary force sought after throughout all tests. The data produced by the strain gauge in a fastener is the information required for calculating this tension force. However, a fastener can experience torque, bending, and yielding depending on the type of fastener, the condition of the plates, and the method of tightening. The effect of these forces on the strain gauge data must be understood.

In an effort to simulate these three conditions, four tests evaluated the performance of strain gauges in conventional fasteners. Torque occurs in conventional fasteners due to the rotation of the nut. Any fastener can experience some amount of bending if the plates

Figure 3.1: Sheldon 10" horizontal lathe, 2mm drill bits also shown

Figure 3.2: M-Bond materials, acetone, syringe, BTM gauge, bolt, scale

are initially deformed. Conventional fasteners tightened with the turn-of-nut method usually experienced the most yielding compared to calibrated wrench tightening and direct tension Huck Fasteners. The set up and results of these four tests are discussed in Section 3.3.

Riggleman (1994) conducted a substantial number of tests to evaluate the accuracy of the BTM strain gauge when used to measure tension in conventional and lock-pin and collar fasteners. The additional calibration tests on conventional fasteners reported herein are intended to supplement the work by Riggleman. The fasteners used in this current study were taken from the same lots as those used by Riggleman.

3.2 CALIBRATION TESTS ON CONVENTIONAL A325 FASTENERS

3.2.1 OVERVIEW OF TESTS PERFORMED

The calibration factor is the relationship between the fastener tension and strain gauge output. For each fastener the load and strain data from a series of loadings established a calibration factor. Specifically, a Satec Systems 600 kip tension / compression test machine loaded a BTM strain gauged fastener in the fastener tension jig, as pictured in Figure 3.3. The bolt tension jig with fastener configuration is also pictured in Figure 3.4. The Satec machine was calibrated to a National Institute of Standards and Technology certified load cell (NIST cell). The Satec loaded each conventional fastener to 40 kips using 10 kip increments. A digital data acquisition system consisting of a Hewlett Packard 3852 data acquisition unit (with digital voltmeter and multiplexer), constant voltage power supply, and a 286 AT IBM compatible computer recorded the data. A total of nine readings provided the data for the calibration factor. The nine readings for a conventional fasteners were taken at the Satec dial readings of 0, 10, 20, 30, 40, 30, 20, 10, and finally 0 kips. These nine readings are referred to as the cycle of calibration loading. A regression analysis of the load and strain data produced a best fit slope of the load versus the strain. The regression line was forced through the origin. This slope is the value used for the

Figure 3.3: Calibration of strain gauged fastener in the bolt tension jig

Figure 3.4: Bolt tension jig with fastener configuration

calibration factor, measured in kips. This calibration factor, when multiplied by the recorded strains of the fastener, equates to tensile loads measured in kips. Figures 3.5a and 3.5b show sample plots used for this regression.

Initially, fasteners were cycled only once to obtain data for the calibration factor. When a fastener was cycled for a second time, slight variation in this calibration factor was observed. This indicated that the tension and strain relationship for other fasteners might be different when loaded for a second time, as in a connection test. To evaluate this variance, single fasteners were cycled numerous times. The 14 tests discussed in Section 3.2.2 show some possible reasons for calibration factor variance, and indicate the steps taken to reduce this variance.

3.2.2 RESULTS OF CALIBRATION TESTS

The evaluation of calibration factor variance involved using 14 conventional fasteners. As described in Section 3.2, a cycle of loading (0, 10, 20, 30, 40, 30, 20, 10, 0 kips) produced the data to calculate the calibration factor. Each fastener experienced between 5-12 cycles of loading to investigate the changes in its calibration factor.

Initially, three 4-1/4" conventional fasteners were cycled eight times through the calibration loading. Each displayed different trends in calibration factor variance. Figure 3.5 shows the % change of the calibration factor between each cycle. Initially, the temperature of the fastener was not considered a factor in the accuracy of the calibration factor. However, a cold fastener demonstrated a jump in the calibration factor of approximately 3% between the first cycle and the second cycle. The description of cold is used to indicate a fastener at an air conditioned temperature of 70-75 degrees, Fahrenheit. The description of "warm" is used to indicate a fastener at lab temperature, between 85-95 degrees, Fahrenheit.

There are two possible explanations for this influence of temperature on the calibration factor. The cold fasteners exhibited more initial strain per load. There may be some slip between the adhesive and the steel of the fastener. The other possibility is that there is some minor initial elongation in the fastener. More tests are needed to verify these possibilities.

Based on this initial indication of calibration factor variance due to temperature, all remaining fasteners were calibrated at lab temperature. All connections tests were conducted at lab temperature. A series of 11 more fasteners were checked for calibration factor stability. The results of these tests are plotted in Figures 3.6 through 3.8. There appeared to be a general leveling off of the calibration factor after approximately 5 cycles. After making this observation, the remaining fasteners in all subsequent connection tests used the calibration factor from the fifth cycle of loading. In the presentation of connection test results in Chapter 4, all tests used this fifth calibration factor, except the six tests in Sections 4.2.1.1 and 4.2.2.1.

Actual plots of the regression data for the warm and cold 4-1/4" fasteners is shown in Figures 3.5a and 3.5b. These plots show the 1st and 5th calibration factors for these fasteners. All four plots are fairly linear.

To maintain perspective in reference to the above discussion, the following two points are made. For the six tests of Sections 4.2.1.1 and 4.2.2.1, only a few fasteners were calibrated in the "cold" condition. Fasteners were usually moved from an air conditioned room to the lab floor in groups of 12. After calibrating approximately 3 fasteners (30 minutes), the remainder should have been at approximately lab temperature. Therefore, only about 25% of the fasteners in a connection test might have tension values that were low by about 1 kip. Also, the second point is that the variance between the initial and fifth calibration factor of a warm fastener resulted in about a 1/2 kip change in fastener tension values. This 1/2 kip difference is noted at a load of 40 kips. Therefore, the six tests in question might vary by about 1/2 kip, due to not using the fifth calibration factor.

3.3 STRAIN GAUGE IN BENDING, TORSION, AND YEILDING

A total of four tests (one bolt each) investigated the effects of bending, torsion, and yielding on the accuracy of the BTM strain gauge. For each test a strain gauged 4-1/4" long 7/8" A325 galvanized fastener was placed in a calibrated Skidmore-Wilhelm bolt tension indicator as seen in Figure 3.9, (model # ML). This tension indicator was calibrated to the Satec Systems 600 kip test machine, which was calibrated to the NIST cell mentioned previously. A pressure transducer electronically measured the pressure in the Skidmore-.

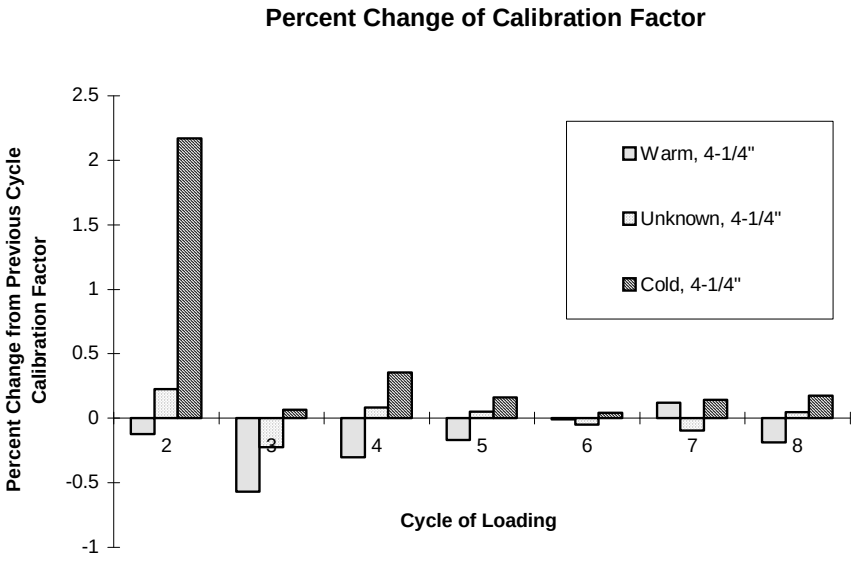


Figure 3.5: Variation of Calib. Factor, 4-1/4" Conv. Fasteners at Different Temperatures

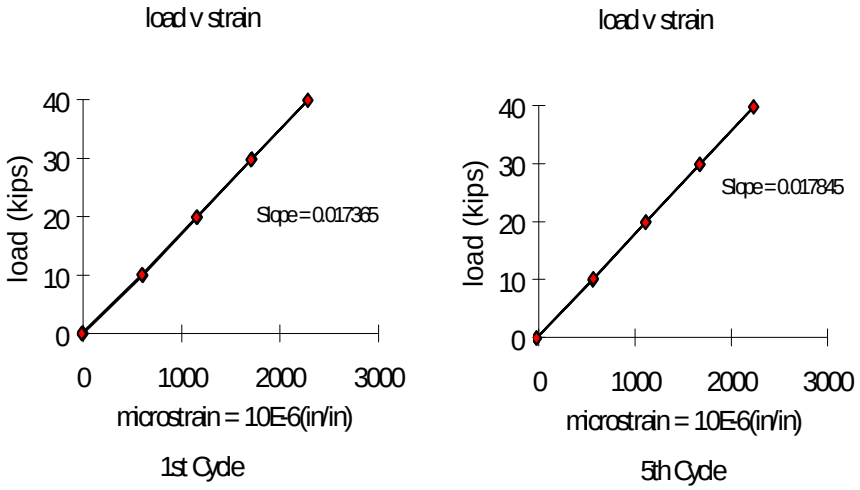


Figure 3.5a: 1st and 5th calibration factor (slope) for cold 4-1/4"

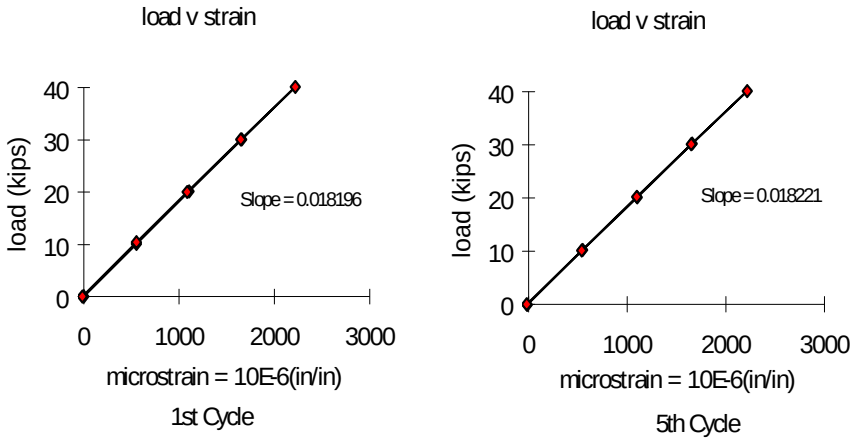


Figure 3.5b: 1st and 5th calibration factor (slope) for warm 4-1/4"

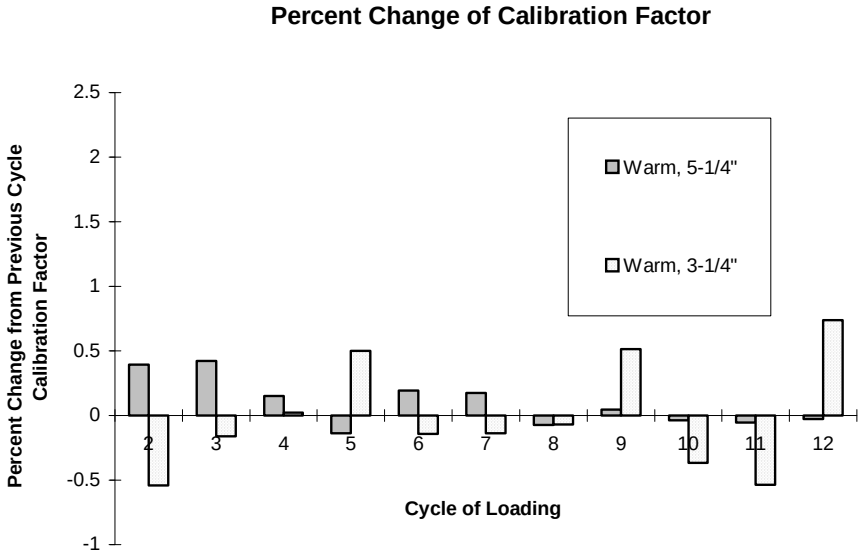


Figure 3.6: Variation of Calib.Factor in 3-1/4" & 5-1/4" Conv. Fasteners, all Warm

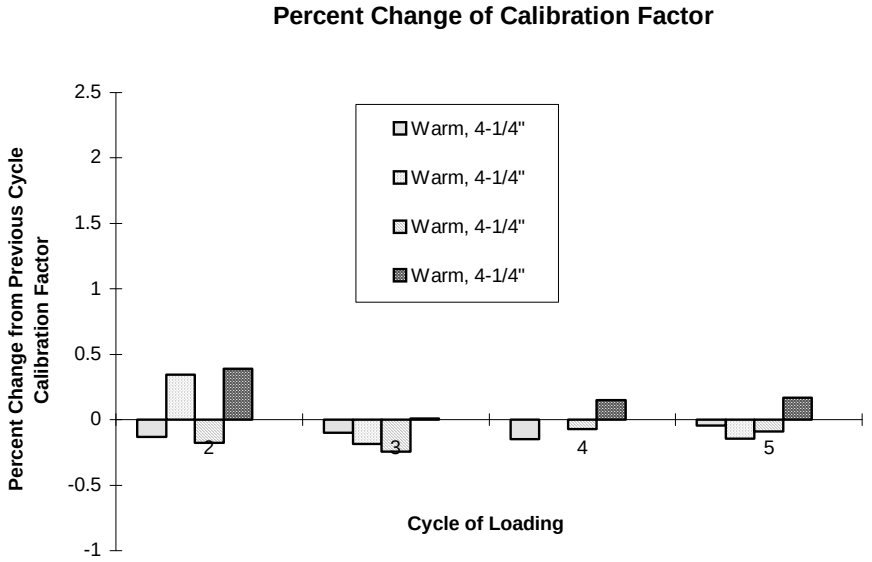


Figure 3.7: Variation of Calib. Factor, 4-1/4" Conv. Fasteners, all warm

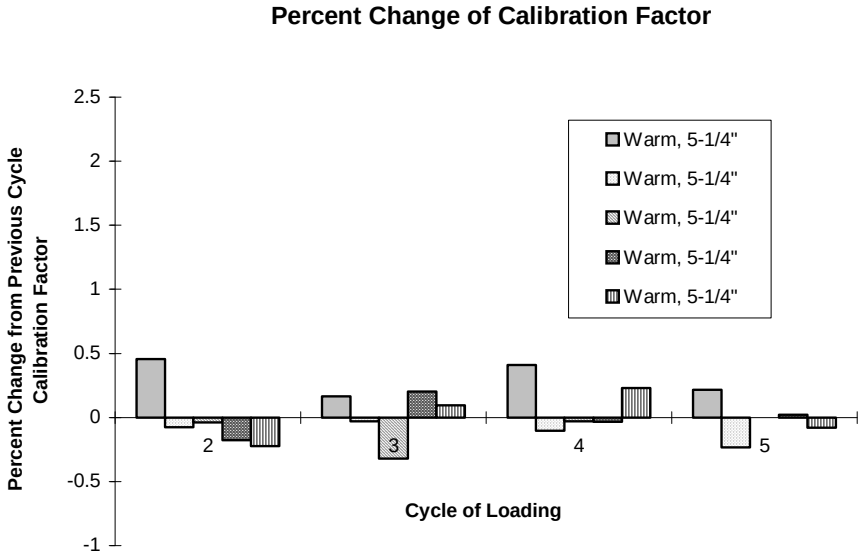


Figure 3.8: Variation of Calib.Factor in 5-1/4" Conv. Fasteners, all Warm

Wilhelm for both calibration and testing. This pressure was used to calculate the tension indicated by the Skidmore-Wilhelm.

3.3.1 OVERVIEW OF TESTS PERFORMED

The intent of each test was to simulate the loading that a fastener may experience while being installed in a connection. The first aspect of loading was that most fasteners were snugged to between 12 and 25 kips. The fastener would then lose some or most of this preload as other fasteners in the connection were snugged. The next loading would be to approximately 40 kips due to a tightening pass. Following that, with some more loss in tension, there might be additional tightening due to a touch-up pass.

The sequence of loading for all six tests followed the same path. A calibrated torque wrench initially snugged each fastener to 20 kips, as seen in Figure 3.10. Then the tension in the fastener was brought to zero with a hydraulic pump releasing the pressure in the Skidmore-Wilhelm. Figure 3.11 shows the hydraulic set-up. This release in tension was to simulate the effect of other fasteners being snugged. The torque wrench then tightened the fastener up to 40 kips. The tension in the fastener was then reduced to 20 kips to again simulate the effects of tightening other fasteners. Following this, the torque wrench simulated a touch-up pass with a series of one to three 1/4 turns of the nut. The 1/4 turn of nut was used to get as much information as possible before possible fracture of the fastener. At the point of apparent yielding, the load in the fastener was decreased to zero by increments of 10 kips. In summary, all loading was done with a torque wrench, and all unloading was done by lowering the pressure in the Skidmore with the hydraulic pump.

The value of torque was recorded for each specified load or nut rotation. Strain gauge and pressure transducer readings were recorded at every change in tension. By comparing the values of the strain gauge, the pressure transducer, and required torque, a series of observations were made regarding the accuracy of the strain gauge readings. These are discussed in Section 3.3.2.

Figure 3.9: Skidmore-Wilhelm bolt tension indicator

Figure 3.10: Initial snugging of fastener in Skidmore-Wilhelm with calibrated torque wrench

Figure 3.11: hydraulic pump set-up for releasing pressure in Skidmore-Wilhelm during strain gauge test

3.3.2 RESULTS OF BENDING, TORSION, AND YIELDING TESTS

Each fastener was subjected to one of four distinct conditions to observe the effects of torsion and bending. Using an ASTM A563 Grade DH nut (lubricated and galvanized) or a non-galvanized and unlubricated nut constituted two conditions for torsion comparison. The unlubricated nut was expected to induce higher torsion forces. The other two conditions involved using a beveled washer in one test and only flat washers in the other test. A beveled washer of 2.86 degrees simulated the maximum bending experienced by a fastener in 3mm deformed plates. Five figures for each test illustrate the values of tension, torque, and fastener yielding.

The initial figure for each test is a plot of BTM strain gauge loads and Skidmore-Wilhelm loads measured with a pressure transducer. Both values are calibrated to the NIST cell, and are measured in kips. They are plotted along the recorded load values indicated by the dial of the Skidmore-Wilhelm. The dial served as a reference point for the initial target loads of 0, 20, 0, 40, 20 kips and the unloading values of 40, 30, 20, and 0 kips. The three 1/4 turn-of-nut rotations occur after the hydraulic pressure release down to 20 kips. The intent of the 1/4 turns is to simulate the loading of the fastener in a final tightening pass. The value of 1/4 of a turn is used solely for the purpose of taking incremental readings of torque and tension. The dial readings for each 1/4 rotation of the nut are on the longitudinal axis of the plot between the initial target values and the unloading values.

The second figure for each test is a bar graph of torque required for each tightening. For each test there are between five and six tightening passes done with the 600 ft lb torque wrench. Each test required initial fastener tightening to the target loads of 20 and 40 kips. The remaining fastener tightening was due to the subsequent 1/4 rotations of the nut. The method of getting torque wrench values required gradual increases in the applied torque until achieving the target loads or the 1/4 turn. Torque values above 600 ft lb required the use of a 4X torque multiplier. The second figure of each test shows the torque required compared to the same Skidmore-Wilhelm dial readings used in the first figure.

The final three figures for each test show the changes in the diameter of the unthreaded shank of each fastener. This portion of the fastener is of particular interest because the BTM strain gauge is located at the core of the unthreaded shank. It is indicated on the diagram of each figure. The same type of calipers used to measure plate deformation

provided the information on diameter changes. Specifically, the diameter of the unthreaded shank was measured at 15 locations. The six corners of the fastener head provided the points for three imaginary planes cutting through the longitudinal side of the fastener. Five levels (every 1/4" below the head of the bolt) along the longitudinal axis of the unthreaded shank provided the location for measuring each of the diameters at the three planes. The measurements of the diameter before and after the test provide the comparison illustrated in the three figures. The comparison shows a reduction in diameter of the fastener. This reduction of diameter is greatest near the threads. It is assumed that most of the yielding occurs in the threads, however this shows some yielding in the unthreaded shank as well.

3.3.2.1 TORQUED TENSION TEST WITH LUBRICATED NUT

As described in Section 3.3.1, a 4-1/4" conventional fastener was placed in the Skidmore-Wilhelm for tension and strain gauge comparison. This test used a lubricated nut with ten hardened flat washers. Figure 3.12 shows very close agreement between the tension values of the BTM strain gauge and the pressure transducer in the Skidmore-Wilhelm. The BTM gauge measured about 1-1.5 kips higher than the Skidmore value after the first 1/4 rotation of the nut. The Skidmore indicated a tension of 49 kips. After another 1/4 rotation of the nut, apparent yielding in the threads caused a slight decrease in tension as indicated by both the BTM gauge and the Skidmore. Upon complete unloading, no residual stress was indicated in the BTM gauge. Figures 3.14 through 3.16 show that there was some permanent necking of the unthreaded shank of the fastener, with no apparent effect on the BTM gauge. Necking of the threaded portion of the fastener is visible in the Figure 3.17, showing the tested fastener on the left. Also apparent is the amount of stretching that took place compared to the other fastener in the picture.

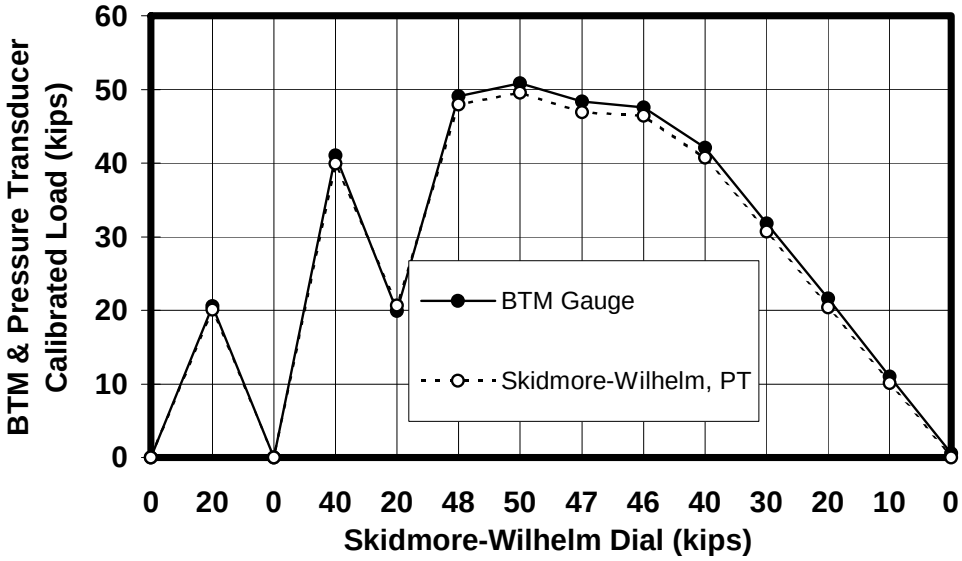


Figure 3.12: **BTM Gauge and Skidmore Load Comparison, Lubricated Nut and Flat Washer**

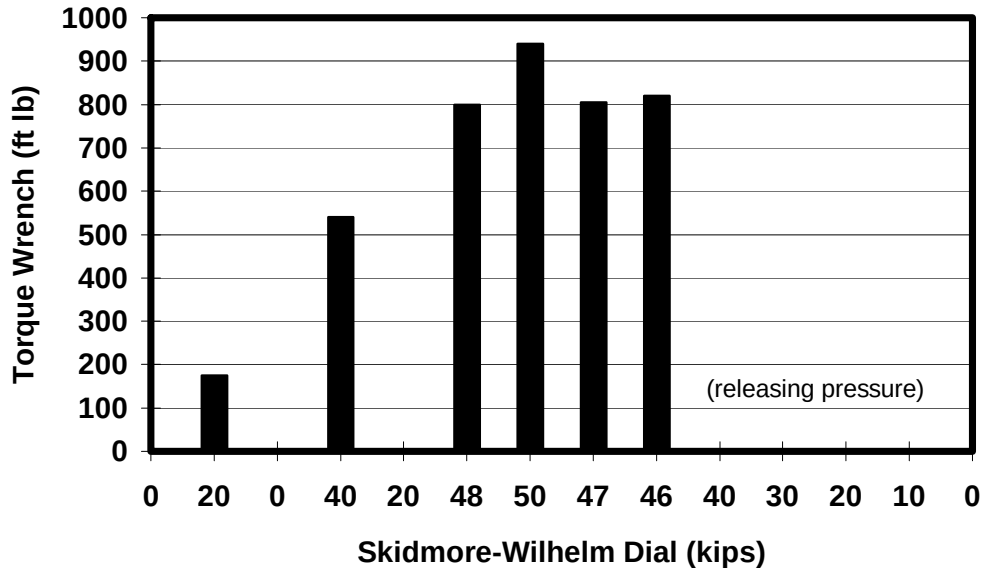


Figure 3.13: **Torque for Each Tightening of Fastener, Lubricated Nut and Flat Washer**

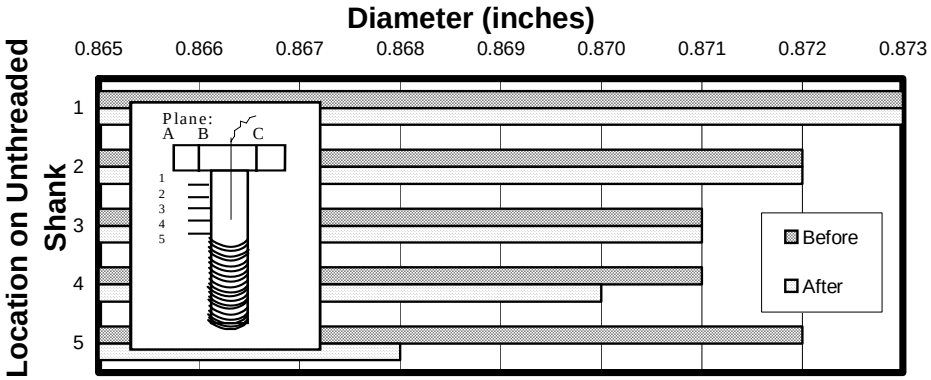


Figure 3.14: **Before/After Diameters in Plane A, Lubricated Nut, Flat**

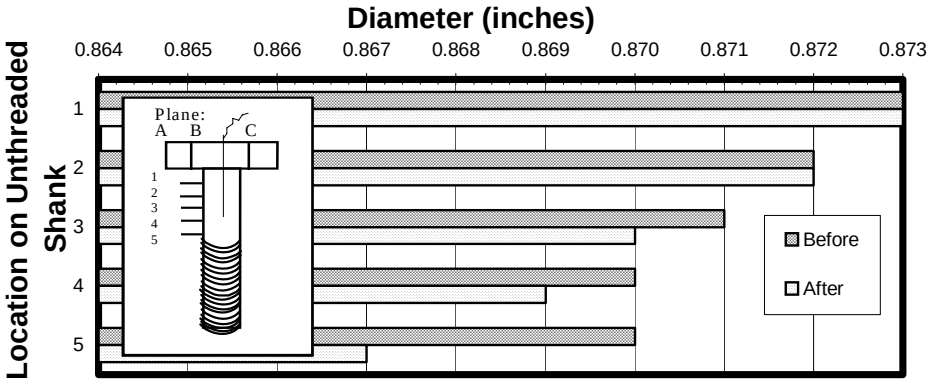


Figure 3.15: **Before/After Diameters in Plane B, Lubricated Nut, Flat**

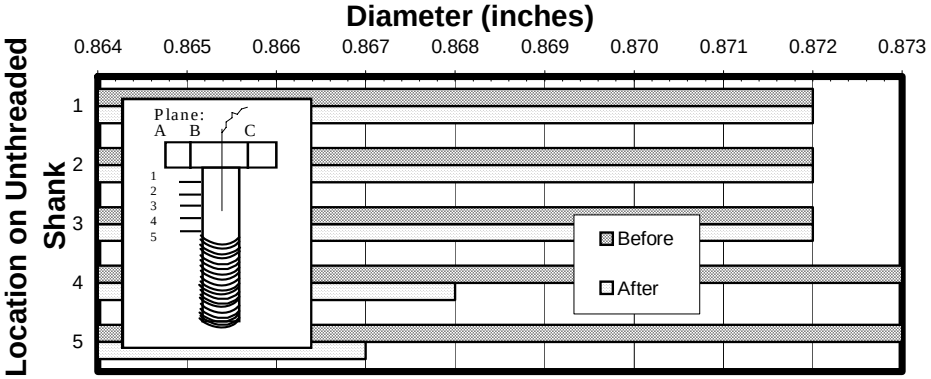


Figure 3.16: **Before/After Diameters in Plane C, Lubricated Nut, Flat**

Figure 3.17: Necking from TORQUED TENSION TEST WITH LUBRICATED NUT (left) Slight Bending from TORQUED TENSION TEST WITH UNLUBRICATED NUT AND BEVELED WASHER (right)

3.3.2.2 TORQUED TENSION TEST WITH LUBRICATED NUT AND BENDING

This test used a lubricated nut, a beveled washer and 8 hardened flat washers. Figure 3.18 shows a picture of the fastener and all washers in the Skidmore-Wilhelm tension indicator. Figure 3.19 shows a consistent difference of about 1 kip between the BTM strain gauge value and the value indicated by the Skidmore-Wilhelm. The BTM gauge indicates the higher tension load. A residual strain corresponding to about 1 kip of fastener tension also appeared in the BTM strain gauge upon complete unloading. In is not known as to when this residual strain developed. Normally, residual strain is considered an indication of yielding. However, this would indicate possible yielding at the initial 20 kip load. This yielding may be due to the bending of the fastener. Figures 3.21 through 3.23 show that there was some permanent necking of the unthreaded shank of the fastener. Also, the fastener appeared to be permanently bent in the threaded portion of the fastener. This bending is similar to the shape of fastener on the right side shown on Figure 3.17. The actual fastener pictured is from the test described in Section 3.3.2.4.

3.3.2.3 TORQUED TENSION TEST WITH UNLUBRICATED NUT

This test used an unlubricated nut with 9 hardened flat washers. Figure 3.24 shows a variable difference of about 14-21 kips between the BTM strain gauge value and the Skidmore-Wilhelm value for tension. This difference was apparent at the first 40 kip loading of the fastener. The BTM gauge measured 62 kips of tension, indicating possible yielding. A 16 kip value also appeared as residual strain in the BTM strain gauge upon complete unloading. In is not known when this residual strain developed. The third curve on Figure 3.24 is the original BTM gauge values with the residual load of 16 kips subtracted from it. This “corrected” BTM gauge value does not match the Skidmore tension loads for the dial values of 40, 20 and 45 kips. There is a 2-5 kip difference between the measured loads. However, for the following two 1/4 turns and unloading increments, the values agree very well.

At this point it is critical to note that this residual strain is subtracted from the strain recorded in the fastener if an adjustment of over 1 kip results. This process was used

Figure 3.18: the beveled washer and 8 flat washers in Skidmore-Wilhelm tension indicator

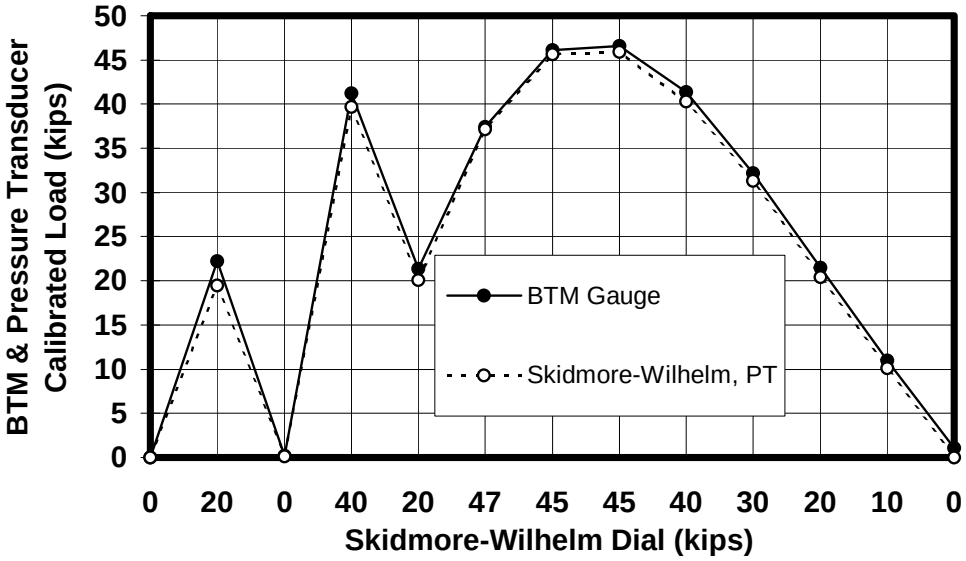


Figure 3.19: BTM Gauge and Skidmore Load Comparison, Lubricated Nut and Beveled Washer

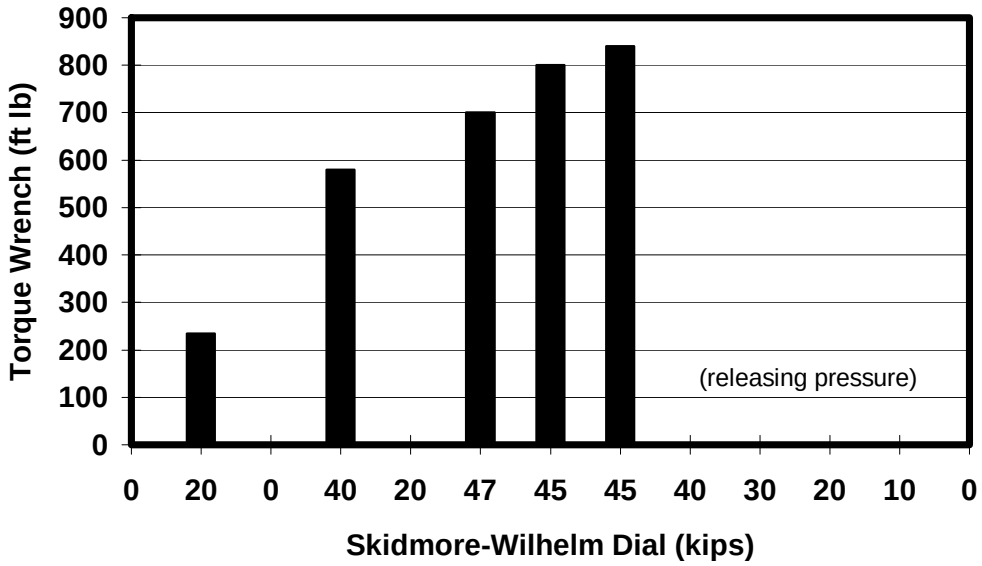


Figure 3.20: Torque for Each Tightening of Fastener, Lubricated Nut and Beveled Washer

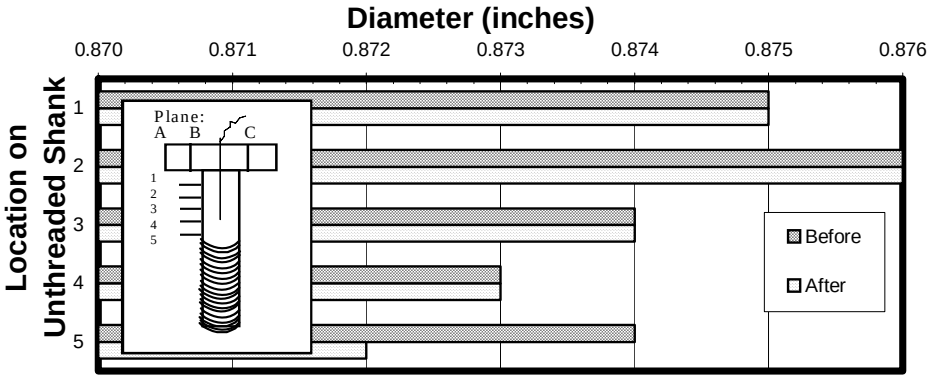


Figure 3.21: **Before/After Diameters in Plane A, Lubricated Nut, Beveled**

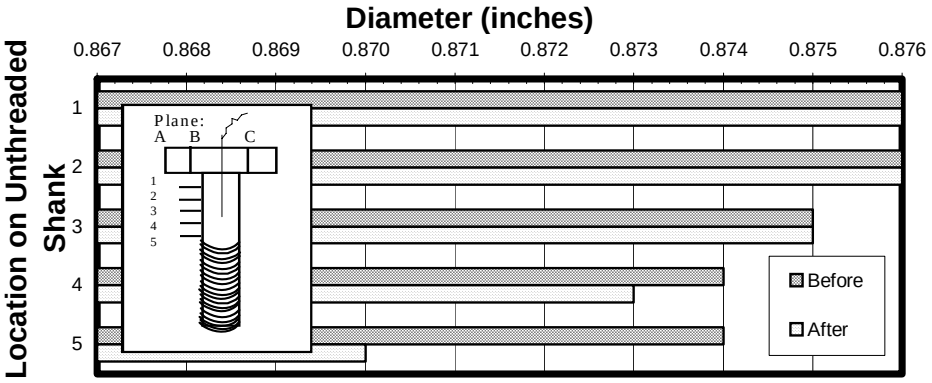


Figure 3.22: **Before/After Diameters in Plane B, Lubricated Nut, Beveled**

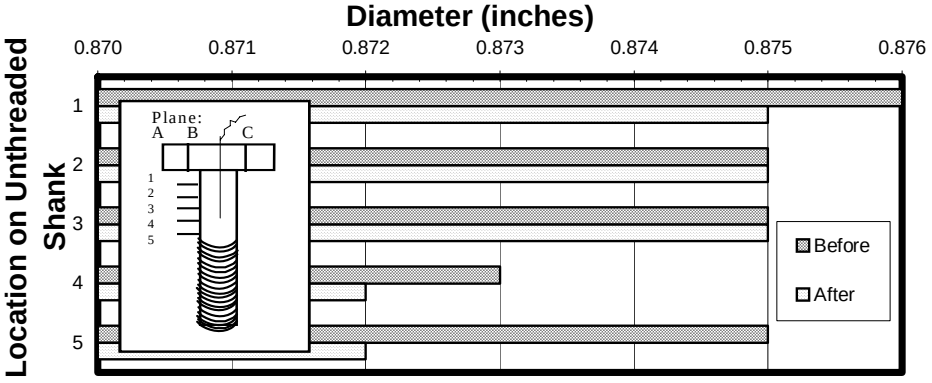


Figure 3.23: **Before/After Diameters in Plane C, Lubricated Nut, Beveled**

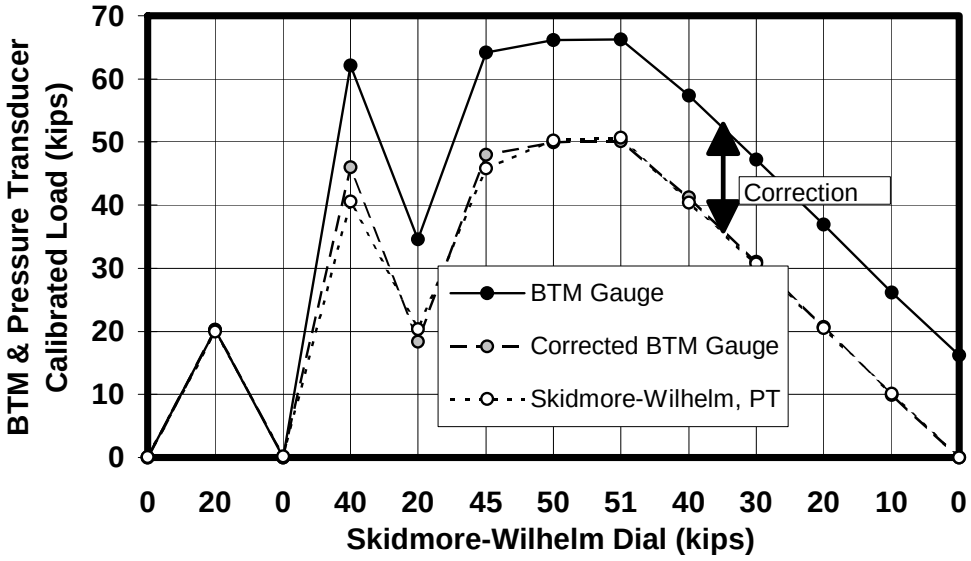


Figure 3.24: BTM Gauge and Skidmore Load Comparison, Unlubricated Nut and Flat Washer

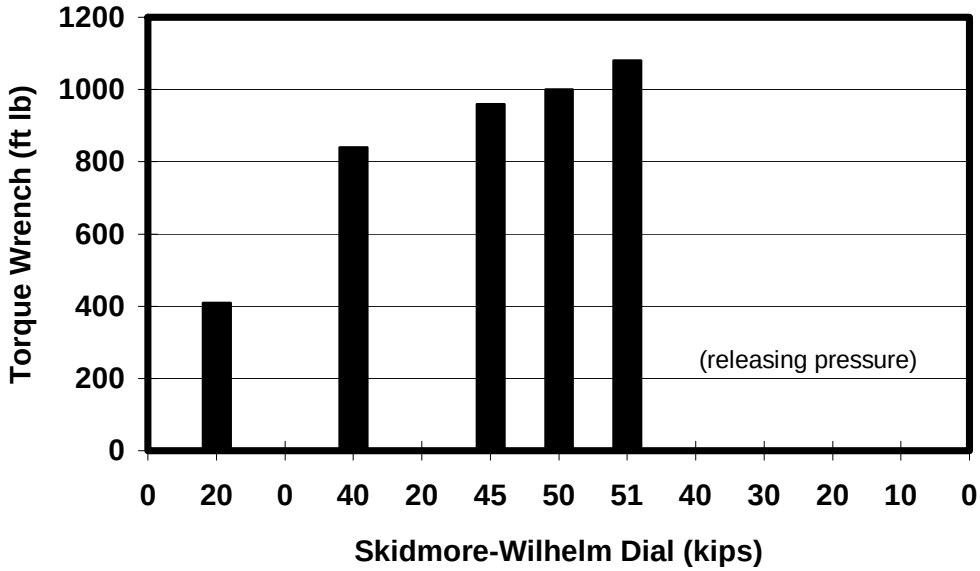


Figure 3.25: Torque for Each Tightening of Fastener, Unlubricated Nut and Flat Washer

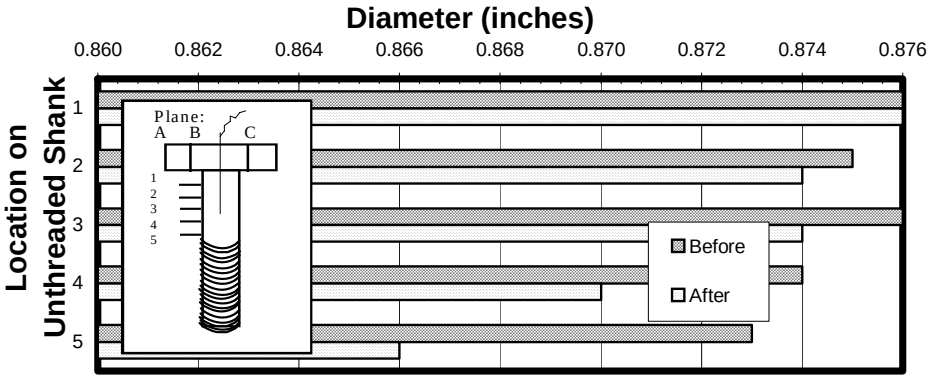


Figure 3.26: **Before/After Diameters in Plane A, Unlubricated Nut, Flat**

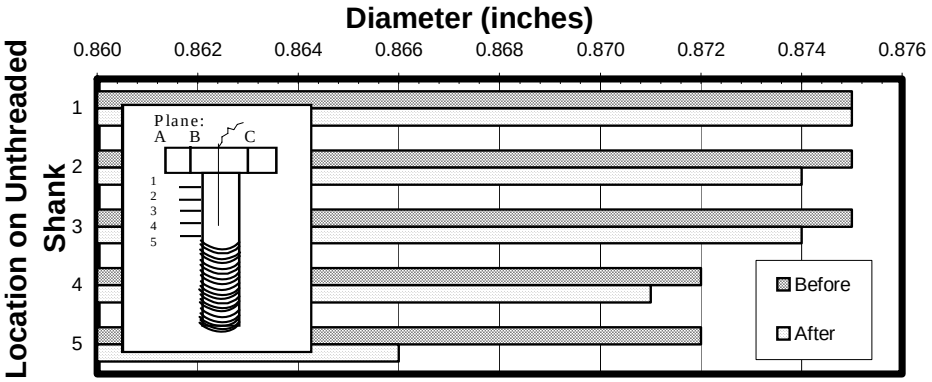


Figure 3.27: **Before/After Diameters in Plane B, Unlubricated Nut, Flat**

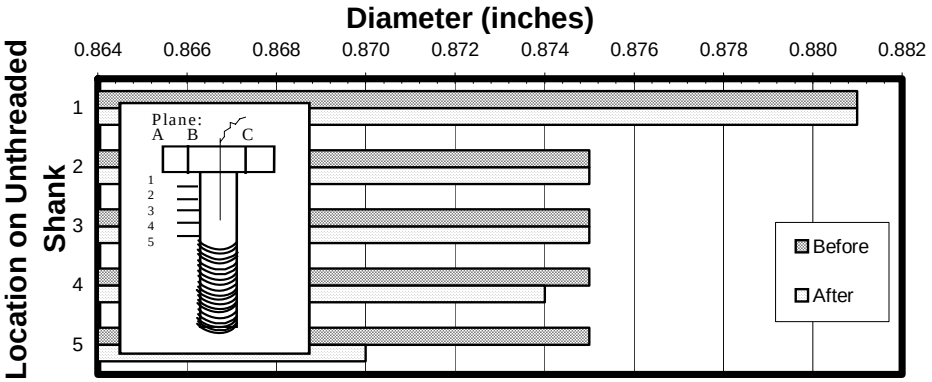


Figure 3.28: **Before/After Diameters in Plane C, Unlubricated Nut, Flat**

for all tests. The residual strain is subtracted from all the strains of a fastener recorded after the last tightening of the fastener. Any attempt to adjust values before the last tightening is subject to error because the actual point of residual strain development is unknown. Figure 3.24 offers a good example of this. The values of load for the corrected BTM and pressure transducer in the Skidmore do not really match until after the final 1/4 turn of nut.

It is interesting to note that the steady increase in torsion indicated in Figure 3.25 does not seem to affect the closeness of the BTM gauge load and Skidmore load. Figures 3.26 through 3.28 show that there was some permanent necking of the unthreaded shank of the fastener. There seems to be evidence that this fastener had more of a reduction in the diameter of the unthreaded shank when compared to the fastener in Section 3.3.2.1 Of the 15 measurements taken, 10 show a reduction in diameter as compared to 7 measurements for the fastener of Section 3.3.2.1. This might be considered a way to evaluate the likelihood of yielding in the unthreaded portion of the fastener when all load was removed.

3.3.2.4 TORQUED TENSION TEST WITH UNLUBRICATED NUT AND BENDING

This test used an unlubricated nut with beveled washer and 8 hardened flat washers. Figure 3.29 shows minimal difference between the BTM strain gauge value and the Skidmore-Wilhelm value for tension. In fact the only difference is at the 40 and 20 kip loadings, as well as the first 1/4 rotation of the nut. The difference is between 1-2 kips. There was no residual strain in the BTM strain gauge upon complete unloading. Figure 3.30 indicates the highest torque values of all 4 tests. This may indicate that torsion has little effect on the BTM strain gauge under these conditions. Figures 3.31 through 3.33 show that there was some permanent necking of the unthreaded shank of the fastener. Also, the fastener was permanently bent in the threaded portion of the shank. Figure 3.17 shows the fastener pictured on the right.

3.3.3 CONCLUSIONS FROM TESTS

Of the three conditions induced (bending, torsion, and yielding), only yielding was taken into account during the actual connection tests in Chapters 4 and 5. Bending does not seem to affect the accuracy of the strain gauge, as evident in the tests with the beveled

washer. The increase in torsion for the tests with the unlubricated nut does not seem to affect the strain gauge accuracy either.

During a connection test residual strain was evident in some fasteners after complete unloading. This residual strain took the form of very small negative values and sometimes larger positive values. The negative numbers, indicating the fastener had somehow compressed, were ignored. However, if a positive residual strain equated to more than 1 kip, it was subtracted from the point of suspected yielding. For example, using Figure 3.24, upon unloading the fastener at the end of a connection test, the strain gauge indicates a positive residual strain. When this strain is multiplied by the calibration factor the result is 16 kips. This 16 kips is subtracted from all the tension loads experienced by the fastener after and including when it was last tightened. Since the BTM gauge indicates 66 kips of tension upon final tightening 16 kips would be subtracted from the 66 kips and all load readings after. The result is a corrected load value. It is an assumption that the residual strain developed at the point of last tightening.

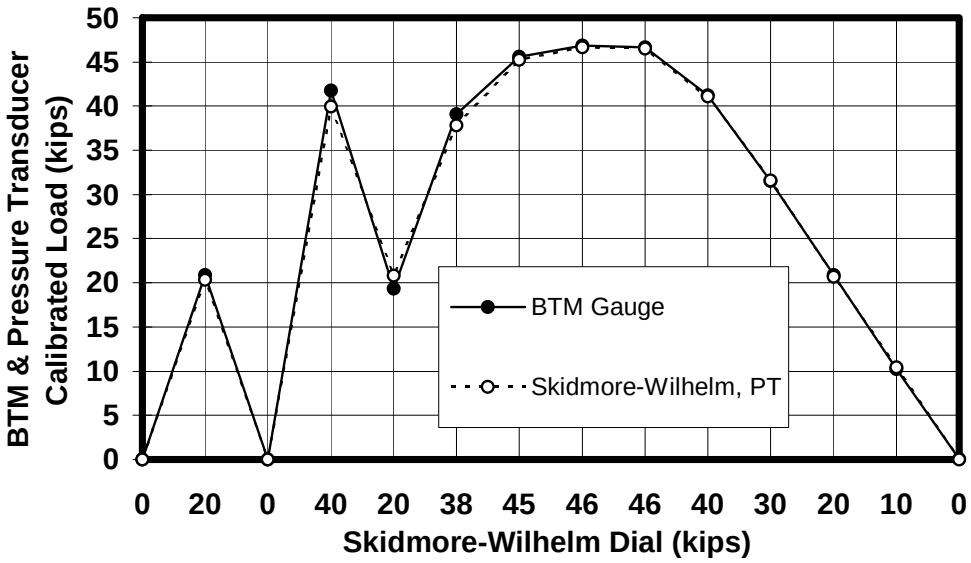


Figure 3.29: BTM Gauge and Skidmore Load Comparison, Unlubricated Nut and Beveled Washer

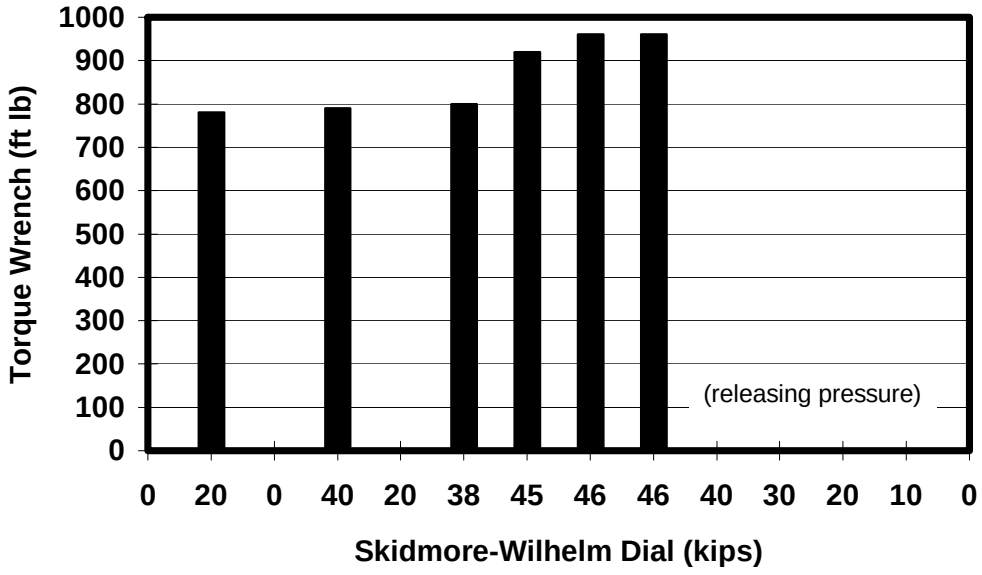


Figure 3.30: Torque for Each Tightening of Fastener, Unlubricated Nut and Beveled Washer

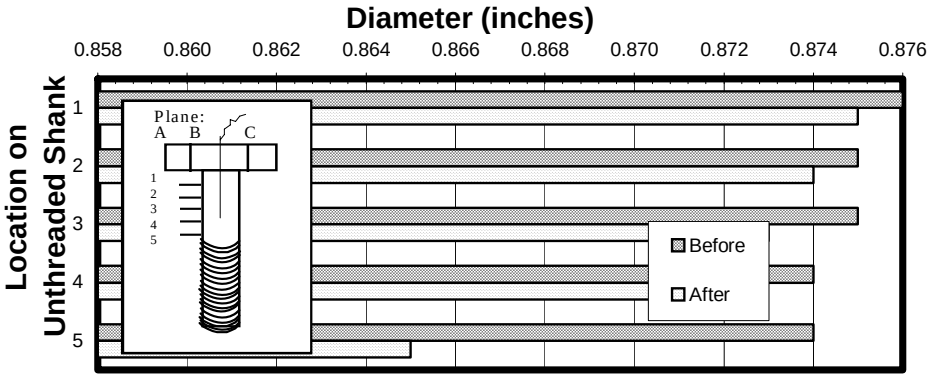


Figure 3.31: **Before/After Diameters in Plane A, Unlubricated Nut, Beveled**

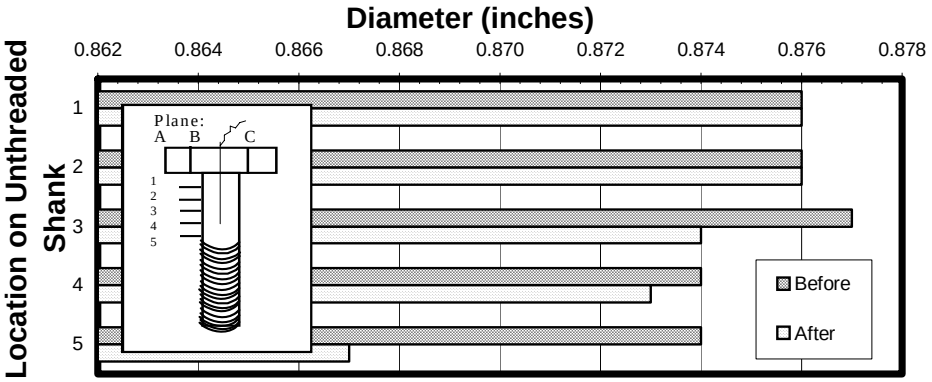


Figure 3.32 : **Before/After Diameters in Plane B, Unlubricated Nut, Beveled**

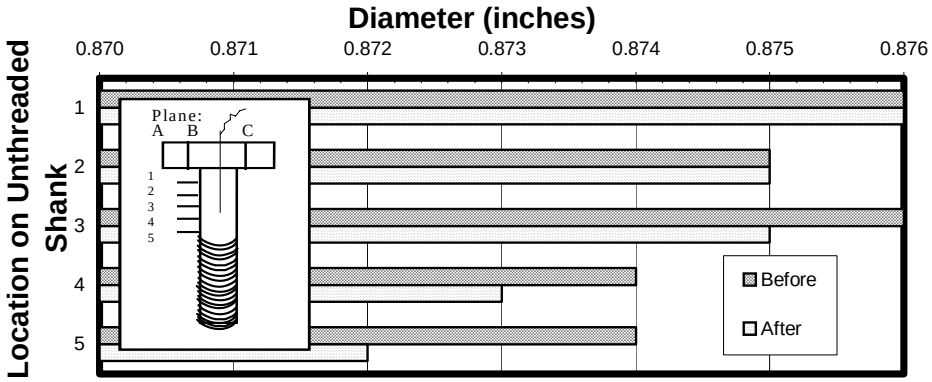


Figure 3.33: **Before/After Diameters in Plane C, Unlubricated Nut, Beveled**

4. CHAPTER 4
CONNECTION TESTS WITH CONVENTIONAL A325 FASTENERS

4.1 GENERAL

All 25 conventional fastener tests consisted of 7/8" diameter high-strength ASTM A325 galvanized bolts. Twelve bolts connected three plates of ASTM A572 Grade 50 steel, producing a slip-critical lap splice connection. The mill test certificate indicated yield stresses ranging from 59.2 ksi to 55.2 ksi for the plates. Three connection grips were evaluated. Figure 4.1 identifies the three bolt lengths and their respective connection (grip) thicknesses. Figure 4.2 highlights the dimensions of the connection and the numbered rows of bolts.

Bolt Length (inches)	Total Grip (inches)	Thickness of Interior Plate (inches)	Thickness of Exterior Plates (inches)
3-1/4	2	1	1/2
4-1/4	3	1-1/2	3/4
5-1/4	4	2	1

Figure 4.1: Bolt Lengths and Grip Thickness

The bolts, nuts and washers satisfied the required ASTM specifications. Specifically, the bolts met ASTM A325-93 standards. Direct tensions tests, rotational capacity tests, and Rockwell hardness tests verified this compliance. Nuts were manufactured to the requirements of ASTM A563 Grade DH, and washers were within the standards of the ASTM A436 specifications. All fastener assemblies consisted only of mechanically galvanized bolts, nuts and washers. All fastener components used in these tests were from the same production lots as those used by Riggleman (1994).

All tests involved a deformed interior plate. As described in Chapter 2, the single curvature interior plate produced a 3mm or 6mm gap between itself and the top exterior.

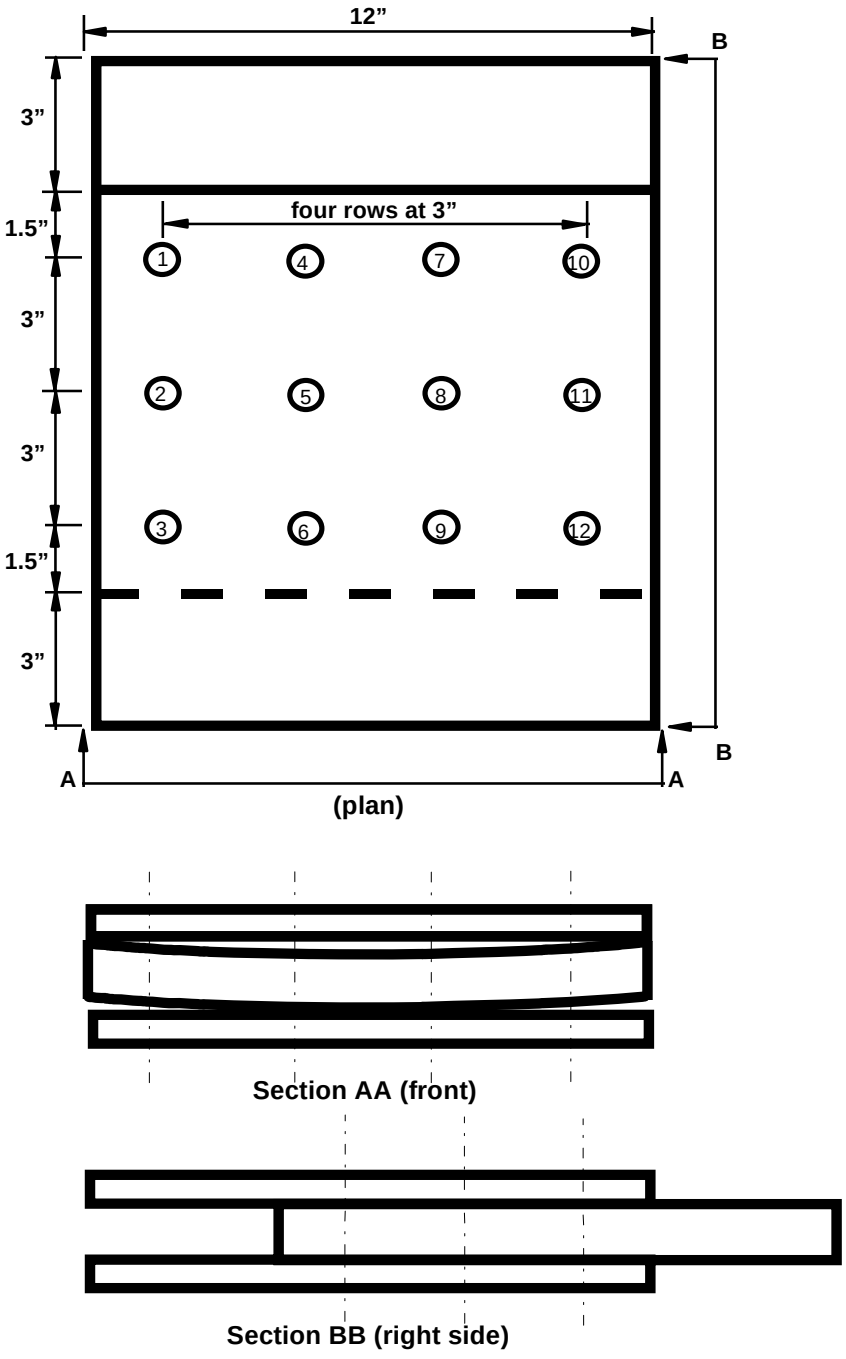


Figure 4.2: **Rows of fasteners**

plate. This out-of-flatness is well within the limit (9.5mm) that the ASTM A6 specification allows for steel plates.

The three primary components of a test set-up were the bolted connection, the support frame, and the data acquisition system. Figure 4.3 shows a typical layout of these components. C-clamps and steel blocks braced the connection against rotation during fastener tightening, as seen in Figure 4.4. Only the force of the tightening fasteners influenced the joining of the plates. Each bolt in the connection had a BTM strain gauge epoxied within the core of the unthreaded shank. Throughout the tightening sequence strain readings were constantly recorded with the data acquisition system for computation of fastener tensions.

The presentation of fastener tensions (test results) follows the same format for each test. For each series of tests, summary tables indicate four statistics for each pass conducted on the bolts. There were three possible passes for each test. The snugging pass was always followed by a tightening pass. If the resulting tensions were low, a touch-up pass followed the tightening pass. Of the four statistics, the first indicates the Average Final Fastener Tension. This is the average tension that existed in all twelve fasteners upon completion of a snugging, tightening, or touch-up pass. The second statistic identifies the average initial tension experienced by each bolt after it was snugged, tightened, or touched-up. The third and forth statistics show the average loss between an initial snugging, tightening, or touch-up tension in each bolt and the final tension upon completing the pass. Specifically, the third statistic is an average tension loss experienced by the first two rows snugged, tightened, or touched-up. The forth statistic is the average tension loss experienced by the last two rows snugged, tightened, or touched-up. All four statistics have their respective standard deviations indicated.

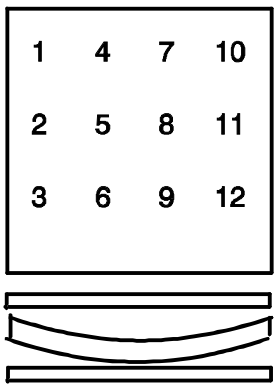
Appendix B contains five figures per test that present tension measurements in each bolt. The first figure shows the complete history of all bolt tensions throughout the sequence of snugging, tightening, and touch-up during a test. The second figure is a bar chart of final tensions for each bolt at the end of the test. The remaining three figures graphically show the tension histories experienced by three selected fasteners. The tensile load history of a fastener is plotted throughout a pass. The first fastener snugged is always

Figure 4.3: Typical test set-up: bolted connection, support frame, and data acquisition system

Figure 4.4 Support frame for bolted connection during test

one of the three bolts graphically represented. The pattern of tightening determines the remaining two bolts.

Figure 4.5 illustrates the numbering template used for all tests. While this template is the same for each test, the three patterns of tightening follow three different sequences of tightening. The bolt numbers underlined and in bold print indicate the bolts that are graphically presented in the tensile load history figures.



Numbering Template

Tightening Pattern	Sequence of Tightening
Middle to Outside	**4**,5,6,7,**8**,9,1,**2**,3,10,11,12
Left to Right	**1**,2,3,4,**5**,6,**7**,8,9,10,11,12
Outside to Middle	**1**,2,3,**10**,11,12,4,**5**,6,7,8,9

Figure 4.5: Bolt Numbering Template and Tightening Pattern Sequences

Six variables identify each of the specific tests. These variables indicate the type of fastener, the amount of plate deformation, the tightening method used, the amount of snugging applied before tightening, the grip thickness of the connection, and the pattern used in tightening. The eleven digit syntax is defined below:

1st Digit: Type of fastener

C: Conventional fasteners (for all tests in this chapter)

H: Huck C50L fasteners (for all tests in Chapter 5)

2nd Digit: Plate condition

D: Deformed interior plate (for all tests)

F: Flat plates

3rd Digit: Middle gap created by single curvature interior plate before loading

3: 3mm gap between bent interior plate and top flat plate

6: 6mm gap between bent interior plate and top flat plate

4th & 5th Digits: Method of Installation

CW: Calibrated Wrench method

TN: Turn-of-Nut method

NS: No snug (for one Huck test only)

CS: Snug with 4 conventional fasteners before installing Huck fasteners

6th & 7th Digits: Snug tension applied before tightening method

12: 12 kip tension

25: 25 kip tension

41: 41 kip tension

8th Digit: Grip thickness of connection

2: 2 inch grip

3: 3 inch grip

4: 4 inch grip

9th - 11th Digits: Pattern of Tightening

MTO: Middle to Outside

LTR: Left to Right

OTM: Outside to Middle

The label of the first test is CD3TN122.MTO. This describes a conventional fastener test with deformed plates (3mm). The method of tightening the fasteners was turn-of-nut after a 12 kip snugging pass. The thickness of the grip was 2 inches (consisting of the 1 inch interior plate and the 1/2 inch thick exterior plates). The pattern of tightening was from the middle fasteners to the outside fasteners.

4.2 3MM DEFORMED PLATES

Eighteen tests involved the use of 3mm deformed plates. Prior to fastener tightening, the 3mm gap existed between the bent interior plate and the flat exterior plate on top. Two methods of fastener tightening joined the plates within the connection. Nine tests

evaluated the turn-of-nut tightening method and the remaining nine tests evaluated the calibrated wrench tightening method. Each tightening method tested all three grip lengths and all three patterns of tightening.

4.2.1 TURN-OF-NUT INSTALLATION METHOD

The *Bolt Specification* states four critical conditions that must be met when using this method. The first stipulation is that an initial snug tightening of the fasteners will bring the deformed plates together in a "snug tight" condition. The second requirement is that fastener tightening progress from the most rigid part of the connection (the middle two rows for connection used in all tests) to the outside edges. The third stipulation is that subsequent fastener loosening may require more than a single snugging pass of all fasteners. The fourth and most critical requirement is that the method should achieve an initial minimum tension of 39 kips in each bolt. The minimum tension of 39 kips applies to A325 bolts with a diameter of 7/8".

The following nine tests evaluated the effect of using a constant 12 kip tension snugging pass followed by the stipulated rotation of the nut. No additional snugging was applied. This is contrary to the *Bolt Specification* which stipulates follow on snugging passes. A calibrated torque wrench produced a fairly consistent 12 kip tension snug. Before each test, a Skidmore-Wilhelm bolt tension indicator verified the ability of the torque wrench to deliver the specified 12 kip snug. By installing a minimum of 3 fastener assemblies in the tension indicator, the setting on the adjustable torque wrench demonstrated a consistent 12 kip tension. A spud wrench with a 4 foot pipe extension, as seen in Figure 4.6, rotated the subsequent 1/3 or 1/2 turn of the nut required. The 2" grip (3-1/4" fasteners = 3.71 bolt diameters) required a 1/3 turn of the nut rotation after the snugging pass. The 3" grip (4-1/4" fastener = 4.86 bolt diameters) and 4" grip (5-1/4" fastener = 6 bolt diameters) required a 1/2 turn of the nut rotation.

Figure 4.6: 4 foot pipe extension for turn-of-nut tightening

Figure 4.7: 600 ft lb calibrated torque wrench used for calibrated wrench tightening

Two alternative tightening patterns produced results for comparison to the pattern of progressing from the middle of the connection to the outside edges (MTO). These two tightening patterns are described as going from left to right across the pattern (LTR) and as going from the outside edges to the middle of the connection (OTM). All three patterns and their respective tightening sequences appear in Figure 4.4 mentioned previously.

4.2.1.1 MIDDLE TO OUTSIDE, 12 KIP SNUG

Three tests followed the middle to the outside tightening pattern, using 3mm deformed plates applying a 12 kip snug before the turn of the nut tightening method. CD3TN12_.MTO identifies this series of tests. The middle to outside tightening sequence is intended to follow the requirement of progressing from the most rigid part of the connection to the outside edges. Following the specified sequence, all twelve bolts received a 12 kip snug with a calibrated torque wrench. The appropriate 1/3 or 1/2 turn-of-nut concluded the tightening pass.

4.2.1.1.1 TEST RESULTS

Tables 4.1 and 4.2 and Figures B.1 through B.15 summarize the results of the CD3TN12_.MTO series of tests. Table 4.1 demonstrates an apparent decrease in final snug fastener tension as the grip length increased. This occurred even though the average initial snug tension was greater as the grip length increased. The average tension lost in both the first two rows snugged and the last two rows snugged increased with greater grip thickness. The first two rows tightened lost more tension than the last two rows tightened. This seems to indicate that thickness of grip affects the ability of fasteners to maintain an initial snug of 12 kips.

Table 4.2 indicates similar results for the tightening pass. However, there is an apparent discontinuity between the 2” grip and the 3” grip. This may be related to the jump from 1/3 of a turn rotation to 1/2 of a turn rotation. The parameters for a 1/3 turn rotation are for lengths less than or equal to four diameters, or 3.5” for 7/8” bolts. The 2” grip uses 3-1/4” bolts, very near the limit of the maximum length for 1/3 of a turn rotation. This

Test # For Middle to Outside Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD3TN122	7.1	2.9	9.6	1.1	4.5	1.8	0.6	0.2
CD3TN123	5.7	5.0	12.8	0.8	10.2	2.6	4.8	3.3
CD3TN124	5.1	5.3	13.5	0.6	11.9	1.4	5.9	4.4

Note: All values in Kips

Table 4.1: Summary of fastener load results for CD3TN12_.MTO series tests - snugging pass

Test # For Middle to Outside Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD3TN122	51.9	2.9	52.8	2.6	1.1	0.4	0.7	0.3
CD3TN123	54.2	5.5	55.8	4.5	2.4	1.2	0.9	0.3
CD3TN124	50.0	11.0	53.1	7.3	5.7	4.2	0.7	0.5

Note: All values in Kips

Table 4.2: Summary of fastener load results for CD3TN12_.MTO series tests - tightening pass

observation may explain the jump in average final tight fastener tension and the average initial tight fastener tension when comparing the 2” grip and 3” grip. The average tension loss in the 1st two rows tightened increased with grip thickness. The last two rows experienced average losses in tension of less than 1 kip. The standard deviation for the 3” and 4” grips indicates a large scatter in the tension values. There is an apparent increase in this scatter with an increase in grip thickness.

Figure B.11 of test CD3TN124.MTO indicates a significant drop in the tension of fastener #4 and fastener #6 after the completion of the tightening pass. With a snug tension of 12 kips the thicker grip may allow a larger gap to exist between plates as compared to thinner grips. This may be an indication of the limit of the turn-of-nut method following a single 12 kip snugging pass. According to the *Bolt Specification*, the intent to the turn-of-nut method is for a direct loading of the fastener, not the closing of a gap. Only the 4” grip resulted in any fastener final tensions below 39 kips. Fasteners #4 and #6 were both below 39 kips at the completion of this test. The average final fastener tension, however, was well above 39 kips.

4.2.1.2 LEFT TO RIGHT, 12 KIP SNUG

Three tests followed the left to right tightening pattern, using 3mm deformed plates applying a 12 kip snug before the turn-of-nut tightening method. CD3TN12_.LTR identifies this series of tests. The left to right tightening sequence is in variance with the *Bolt Specification* requirement of tightening from the most rigid portion of the connection to the free edges. A calibrated torque wrench applied the 12 kip snug to all twelve bolts, followed by the appropriate 1/3 or 1/2 turn-of-nut.

4.2.1.2.1 TEST RESULTS

Tables 4.3 and 4.4 and Figures B.16 through B.30 summarize the results of the CD3TN12_.LTR series of tests. Table 4.3 shows a decrease in Average Final Snug Fastener Tension with an increase in grip thickness. This is more apparent between the 2” grip and the 3” grip. The 3” and 4” grips have very similar values for final snug tensions

Test # For Left to Right Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD3TN122	8.7	2.6	11.9	0.9	4.1	1.8	2.8	2.9
CD3TN123	4.1	4.2	11.7	0.8	7.2	3.2	9.7	2.4
CD3TN124	4.0	3.9	11.6	1.2	7.2	4.1	9.7	1.7

Note: All values in Kips

Table 4.3: Summary of fastener load results for CD3TN12_.LTR series tests - snugging pass

Test # For Left to Right Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD3TN122	52.1	1.9	53.2	1.7	1.2	0.1	1.2	0.4
CD3TN123	55.0	2.2	56.6	1.7	2.5	1.7	1.1	0.5
CD3TN124	42.1	11.0	48.9	9.7	7.6	2.4	7.1	6.5

Note: All values in Kips

Table 4.4: Summary of fastener load results for CD3TN12_.LTR series tests - tightening pass

and average tension losses. The last rows snugged lost slightly more tension than the first rows snugged for both the 3" and 4" grips.

Table 4.4 shows a consistent increase in average tension loss with an increase in grip thickness. There is a jump in the Average Final Tight Fastener Tension of the 3" grip when compared to the 2" grip. The average tension loss of rows tightened is very low,(1-3 kips) for both the 2" and 3" grips. The 4" grip has an average tension loss of over 7 kips for both rows.

Figure B.27 for test CD3TN124.LTR shows an interesting limit regarding the left to right tightening pattern. Fasteners #4, #7, and #10 all fell well below the minimum final tension of 39 kips. These fasteners were the first of their respective rows to be tightened.

4.2.1.3 OUTSIDE TO MIDDLE, 12 KIP SNUG

Three tests followed the outside to middle tightening pattern, using 3mm deformed plates applying a 12 kip snug before the turn-of-nut tightening method. CD3TN12_.OTM identifies this series of tests. The outside to middle tightening sequence is also at variance with the *Bolt Specification* requirement of tightening from the most rigid portion of the connection to the free edges. Each test received a snugging pass of 12 kips and a tightening pass of the appropriate 1/3 or 1/2 turn-of-nut.

4.2.1.3.1 TEST RESULTS

Tables 4.5 and 4.6 and Figures B.31 through B.45 summarize the results of the CD3TN12_.OTM series of tests. Table 4.5 shows a similar trend of decreasing average final snug fastener tensions with an increase in grip thickness. Also, average tension loss of snugged fasteners increased with grip thickness. While the 2" grip test had similar tension losses for both the first two and last two rows tightened, the 3" and 4" grips had greater losses in the first two rows tightened.

Table 4.6 reiterates the trend of increasing tension loss with increasing grip thickness. It may be possible to think of the outside to middle tightening pattern as

Test # For Outside to Middle Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD3TN122	7.7	2.9	11.1	1.5	3.7	1.9	3.9	1.9
CD3TN123	4.7	3.6	11.6	1.2	8.3	2.8	6.5	3.4
CD3TN124	4.4	3.8	11.7	0.9	8.4	3.0	7.5	3.0

Note: All values in Kips

Table 4.5: Summary of fastener load results for CD3TN12_.OTM series tests - snugging pass

Test # For Outside to Middle Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD3TN122	51.8	3.3	52.6	3.6	1.0	0.5	0.9	0.2
CD3TN123	53.2	9.1	54.4	9.3	0.7	0.4	2.0	1.3
CD3TN124	39.5	20.3	46.2	14.6	8.9	8.8	5.3	3.5

Note: All values in Kips

Table 4.6: Summary of fastener load results for CD3TN12_.OTM series tests - tightening pass

"trapping" a gap between tightened rows. Average tension losses in the first row are more than losses for the last row of fasteners tightened.

Figure B.42 of test CD3TN124 .OTM indicates a significant tension loss in fasteners #10, #11, and #12. This resulted in all three being below 39 kips after the test was completed. This outside edge of fasteners indicates that the "trapped" gap may have shifted to the outside edge of the connection as the last two middle rows of fasteners are tightened.

4.2.1.4 TIGHTENING PATTERN COMPARISION

The first nine tests of the turn-of-nut method provide comparisons between the three tightening patterns for all three grip lengths. For the 2" grip, the difference between the Average Initial Snug Fastener Tension and the Average Final Snug Fastener Tension increases in the order of middle to outside (MTO), left to right (LTR) and outside to middle (OTM). The differences are 2.5 kips, 3.2 kips, and 3.5 kips. In other words the loss of fastener tension seems to be the greatest for the OTM pattern of tightening. The results for the 3" grip are not in the same sequence. The OTM pattern had the least difference between the Average Initial Snug Fastener Tension and the Average Final Snug Fastener Tension. For the MTO, LTR, and OTM the differences are 7.1 kips, 7.7 kips, 6.9 kips respectively. Finally, the 4" grip had the opposite trend of the 2" grip. The MTO, LTR, OTM differences are 8.4 kips, 7.6 kips, and 7.3 kips respectively. Therefore, the results do not seem to appreciatively favor any pattern of tightening for the snugging pass.

For the tightening pass, the 2" and 3" grips do not offer any differences greater than 1 kip between the tightening patterns. However, the 4" grip shows more than double the tension loss for the LTR and OTM patterns when compared to the MTO pattern. The differences between the Average Initial Tight Fastener Tensions and the Average Final Tight Fastener Tensions are 3.1 kips, 6.8 kips, and 6.7 kips for the MTO, LTR, OTM patterns respectively. This could be evidence in support of the Middle to Outside tightening pattern, at least for thicker connections.

All fasteners in the 2" grip for each of the three patterns met the required 39 kip minimum after the tightening pass. The 3" grip had only one fastener fall below the 39 kip minimum as noted in Figure B.37 for the OTM test series. The 4" grip saw 3 fastener

tensions fall below the 39 kip minimum for both the LTR and OTM tests. The average final fastener tension was above 39 kips for all tests.

4.2.2 CALIBRATED WRENCH INSTALLATION METHOD

The *Bolt Specification* requires that essentially the same four critical conditions be met as for the turn-of-nut installation method. The difference is that it permits subsequent tightening passes. Snug tight fasteners must bring plates into firm contact with each other. After this initial snug, the calibrated wrench tightening method can begin. The snugging and tightening pattern must progress from the most rigid part of the joint to the free edges. The calibrated wrench must achieve a minimum initial tension of 41 kips in each bolt for the 7/8" diameter bolts.

The following nine tests evaluated the effect of using a 25 kip and 12 kip tension snug pass followed by a 41 kip tightening pass. Six of the nine tests included a 41 kip touch-up pass. The torque wrench was calibrated as specified in the *Bolt Specification*. Before each test, a Skidmore-Wilhelm bolt tension indicator verified the ability of the torque wrench to deliver the specified 12 kip or 25 kip snug and 41 kip tightening. The nine tests used the same three tightening patterns as in the previous turn-of-nut tests.

4.2.2.1 MIDDLE TO OUTSIDE, 25 KIP SNUG

Three tests followed the middle to the outside tightening pattern, using 3mm deformed plates, applying a 25 kip snug before the 41 kip tightening pass. CD3CW25_.MTO identifies this series of tests. Riggleman performed previous calibrated wrench tests but with a 12 kip snug, therefore the following three tests used 25 kip snugging. Following the specified sequence for the middle to outside tightening pattern, all twelve bolts received a 25 kip snug with a calibrated torque wrench. A 41 kip tightening and touch-up pass completed the tests, as seen in Figure 4.7.

4.2.2.1.1 TEST RESULTS

Tables 4.7 through Table 4.9 and Figures B.46 through B.60 summarize the results of the CD3CW25_.MTO series of tests. Table 4.7 shows consistent decrease in Average

Test # For Middle to Outside Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD3CW252	22.6	3.0	24.3	1.9	3.2	2.4	0.2	0.2
CD3CW253	18.9	8.4	26.2	2.3	13.5	3.6	1.3	1.0
CD3CW254	11.0	8.9	25.0	1.5	20.6	5.0	9.1	5.9

Note: All values in Kips

Table 4.7: Summary of fastener load results for CD3CW25_.MTO series tests - snugging pass

Test # For Middle to Outside Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD3CW252	40.9	2.0	41.4	2.1	0.7	0.1	0.5	0.1
CD3CW253	41.0	3.7	41.5	2.9	0.8	1.5	0.5	0.2
CD3CW254	40.8	3.9	42.7	3.1	3.4	2.4	0.4	0.2

Note: All values in Kips

Table 4.8: Summary of fastener load results for CD3CW25_.MTO series tests - tightening pass

Test # For Middle to Outside Pattern	Average Final Touch-up Fastener Tension	Standard Deviation	Average Initial Touch-up Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Touched-up	Standard Deviation	Average Tension Loss in Last Two Rows Touched-up	Standard Deviation
CD3CW252	42.3	1.4	42.6	1.3	0.2	0.1	0.2	0.1
CD3CW253	40.2	2.4	40.2	2.4	0.0	0.2	0.1	0.1
CD3CW254	41.3	3.3	41.5	3.5	0.4	0.0	0.2	0.1

Note: All values in Kips

Table 4.9: Summary of fastener load results for CD3CW25_.MTO series tests - touch-up pass

Final Snug Fastener tensions as the grip thickness increased, even with a fairly consistent Average Initial Snug Fastener Tensions. The average tension loss is dramatic in the first two rows snugged.

Table 4.8 indicates the Average Final Tight Fastener Tensions slightly exceeded the required 39 kips for all grips. The touch-up pass was not really necessary. The minimum 39 kip tension was developed in at least 32 of the 36 bolts tested in the three tests. The average tension loss in the first two rows tightened is minor for all three tests. Table 4.9 shows slight changes in the Average Final Touch-up Fastener Tensions. The 2" and 4" grips have an increase of Average Final Touch-up Fastener Tensions while the 3" grip shows a decrease. All changes are barely more than one kip in magnitude. There is less average tension loss in the rows during the touch-up pass. This is expected with plates in firm contact.

Figures B.46 through B.60 demonstrate a consistent maintenance of tension load after the tightening pass. Of the nine Tensile Load Histories plotted for the CD3CW25.MTO series of tests, not one shows a drop in tension below 39 kips upon completion of the tightening pass.

4.2.2.2 LEFT TO RIGHT, 12 KIP SNUG

Three tests followed the left to right tightening pattern, using 3mm deformed plates applying a 12 kip snug before the 41 kip calibrated wrench tightening method. CD3CW12_.LTR identifies this series of tests. These tests offer a comparison to the results of the CD3TN12_.LTR tests. The differences are the tightening method and the fact that the CD3TN12_.LTR tests did not have a touch-up pass. Following the specified sequence for the left to right tightening pattern, all twelve bolts received a 12 kip snug with a calibrated torque wrench. A 41 kip tightening and touch-up pass completed the test.

4.2.2.2.1 TEST RESULTS

Table 4.10 through 4.12 and Figures B.61 through B.75 show the results of the CD3CW12_.LTR series of tests. The snug statistics of Table 4.10 are almost the same as those of Table 4.3. This is noted as a verification of consistency in the 12 kip snugging

Test # For Left to Right Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD3CW122	8.9	3.3	12.5	1.6	5.1	1.8	2.5	2.6
CD3CW123	4.1	4.2	11.3	1.3	6.1	3.8	9.8	2.3
CD3CW124	4.5	3.4	11.8	0.6	6.5	2.9	9.9	1.6

Note: All values in Kips

Table 4.10: Summary of fastener load results for CD3CW12_.LTR series tests - snugging pass

Test # For Left to Right Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD3CW122	39.9	2.5	40.6	2.4	0.8	0.1	0.7	0.2
CD3CW123	41.7	3.7	43.7	2.2	2.9	2.6	1.3	0.8
CD3CW124	31.4	7.2	41.6	2.0	11.4	1.5	10.7	7.9

Note: All values in Kips

Table 4.11: Summary of fastener load results for CD3CW12_.LTR series tests - tightening pass

Test # For Left to Right Pattern	Average Final Touch-up Fastener Tension	Standard Deviation	Average Initial Touch-up Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Touched-up	Standard Deviation	Average Tension Loss in Last Two Rows Touched-up	Standard Deviation
CD3CW122	41.6	2.7	41.7	2.7	0.2	0.0	0.1	0.0
CD3CW123	43.2	3.3	43.2	3.3	0.0	0.1	0.0	0.1
CD3CW124	40.1	2.8	40.4	2.6	0.5	0.4	0.2	0.2

Note: All values in Kips

Table 4.12: Summary of fastener load results for CD3CW12_.LTR series tests - touch-up pass

pass. For the first tightening pass of the 4” grip, Table 4.11 indicates an Average Final Tight Fastener Tension 7.6 kips below the minimum of 39 kips. Only the last three fasteners of the tightening pass held a tension above 39 kips for the 4” grip. The calibrated wrench method does not supply much tension beyond it’s intended 41 kip load. Riggleman had similar results for the first tightening pass of his 12 kip snug, calibrated wrench test. As expected for the 4” grip, the average tension loss in the first and second rows tightened is greater than that of the 2” and 3” grips.

As recommended by the *Bolt Specification*, Table 4.12 indicates that the Average Final Touch-up Fastener Tension meets the 39 kip requirement for all grips. However, even after this touch-up pass, there was one bolt below the 39 kip minimum for the 2” and 3” grips. There were four bolts that were just below the 39 kip tension for the 4” grip.

4.2.2.3 OUTSIDE TO MIDDLE, 12 KIP SNUG

Three tests followed the outside to middle tightening pattern, using 3mm deformed plates applying a 12 kip snug before the 41 kip calibrated wrench tightening method. CD3CW12_.OTM identifies this series of tests. Following the sequence for the outside to middle tightening pattern, all twelve bolts received a 12 kip snug with a calibrated torque wrench. A 41 kip tightening pass completed the test. A touch-up pass was not conducted.

4.2.2.3.1 TEST RESULTS

Tables 4.13 through 4.14 and Figures B.76 through B.90 show the results of the CD3CW12_.OTM series of tests. An increase in grip thickness caused increased tension loss after the snugging pass. Most tension loss was in the first two rows tightened (on the outside). The tightening pass reflects the same trend as the snugging pass. The Average Final Tight Fastener Tensions for the 2” and 3” grips are above 39 kips. After the tightening pass the 2" grip had one fastener that did not maintain the 39 kip minimum. The 3" and 4" grips had 4 and 8 fasteners, respectively, that did not maintain the 39 kip minimum. The Average Final Tight Fastener Tension for the 4” grip is 37 kips. The 4” grip clearly needed a touch-up pass, however this was not conducted.

Test # For Outside to Middle Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD3CW122	8.6	2.3	11.6	1.2	2.8	1.6	3.7	2.0
CD3CW123	5.4	3.9	11.8	1.0	7.8	2.2	6.0	3.0
CD3CW124	4.4	4.2	12.4	0.9	8.9	2.3	8.5	3.3

Note: All values in Kips

Table 4.13: Summary of fastener load results for CD3CW12_.OTM series tests - snugging pass

Test # For Outside to Middle Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD3CW122	40.9	2.5	41.4	2.5	0.8	0.1	0.4	0.1
CD3CW123	39.9	3.9	40.9	3.1	0.3	0.2	2.2	1.8
CD3CW124	37.0	4.2	42.6	2.3	6.4	2.6	5.8	3.3

Note: All values in Kips

Table 4.14: Summary of fastener load results for CD3CW12_.OTM series tests - tightening pass

4.2.2.4 TIGHTENING PATTERN COMPARISION

The first nine tests of the calibrated wrench method provide comparisons between the three tightening patterns for all three grip lengths. Because the middle to outside (MTO) tests (CD3CW25_.MTO) used a 25 kip snug, Riggleman's CDCW series tests (12 kip snug) will be used for the MTO comparison to the LTR and OTM tightening patterns. The CD3CW25_.MTO series of tests permit evaluation of the difference between the 12 and 25 kips snugging for the MTO pattern. This will be discussed at the end of this section.

For the 2" and 3" grips, the difference between the Average Initial Snug Fastener Tension and the Average Final Snug Fastener Tension does not vary more than 1.5 kips between the MTO, LTR and OTM patterns. However, both the 2" and 3" grip indicate the most tension loss for the LTR pattern. The 4" grip tests show that the LTR and OTM patterns lost more tension than the MTO pattern of tightening. The differences between the Average Initial Snug Fastener Tensions and the Average Final Snug Fastener Tensions are 6.4 kips, 7.4 kips, and 8.0 kips for MTO, LTR, and OTM respectively. The results do not seem to appreciatively favor any pattern of tightening for the snugging pass. With a comparison to the snugging pass of the turn-of-nut method, there does not seem to be any trend for which pattern sustains the most tension after the 12 kip snug pass.

For the tightening pass, the 2" and 3" grips do not offer any differences between the tightening patterns that exceed 1 kip. However, the 4" grip shows nearly double the tension loss for the MTO and LTR patterns when compared to the OTM pattern. The differences between the Average Initial Tight Fastener Tensions and the Average Final Tight Fastener Tensions are 10.1 kips, 10.2 kips, and 5.6 kips for the MTO, LTR, OTM patterns respectively. This could be evidence in support of the Outside to Middle tightening pattern, at least for thicker connections. This is contrary to the findings of the turn-of-nut series of tests.

For Riggleman's MTO pattern of tests, the 2" grip had four fasteners under the required 39 kip minimum after the tightening pass. The 3" and 4" grip MTO tests had 10 and 8 fasteners, respectively, below the 39 kip minimum. The 2", 3" and 4" grips for the LTR pattern of tightening had 2, 2, and 9 fasteners fall below the 39 kip minimum, respectively. The OTM pattern of tightening faired slightly better with the 2" , 3" and 4" grips having 1, 4, and 8 fasteners, respectively, below the 39 kip minimum. This is another

way to look at the results supporting the OTM pattern for the calibrated wrench tightening method.

When comparing the 12 kip and 25 kip snug for the MTO tightening pattern, there are clear indications of which provides a higher final fastener tension . The 2" and 3" grips show similar tension losses to within 1-2 kips for both the snugging and tightening passes. The Average Final Tight Fastener Tensions are higher for the 25 kip snug pass. The 2", 3" and 4" grip Average Final Fastener Tensions are 39.5, 35.4, and 30.4 for the 12 kip snug as compared to 40.9, 41.0, and 40.8 for the 25 kip snug.

4.2.3 TIGHENING METHOD COMPARISION

All the average final snug fastener tensions are fairly similar between the two tightening methods. This is expected since the snugging pass is independent of the subsequent tightening pattern. The Average Final Tight Fastener Tensions were consistently higher for the turn-of-nut method. The turn-of-nut method averaged between 2.6 and 13.3 kips higher Average Final Tight Fastener Tensions for the 18 tests conducted. All turn-of-nut methods produced Average Final Tight Fastener Tensions above 39 kips. The calibrated wrench method resulted in 2 tests averaging below 39 kips. Both were with the 4" grip.

4.3 6MM DEFORMED PLATES

Seven tests involved the use of 6mm deformed plates. Prior to fastener tightening, the 6mm gap existed between the bent interior plate and the flat exterior plate on top. Two methods of fastener tightening joined the plates within the connection. Three tests evaluated the turn-of-nut tightening method using 2", 3", and 4" grips. Four tests evaluated the calibrated wrench tightening method using only the 3" and 4" grips.

4.3.1 TURN-OF-NUT INSTALLATION METHOD

The three tests with the 6mm gap used the same turn-of-nut method described in section 4.2.1. However, the "snug tight" intent of the *Bolt Specification* became very apparent. Two tests (the 2" and 3" grips) used a single snug pass of 12 kips. The 3" grip produced an average final tight fastener tension well below the minimum tension of 39 kips.

The 4” grip test followed the *Bolt Specification* more closely by snugging the fasteners to where the plates appeared to be in firm contact. The fasteners received a total of 3 snugging passes. The first snugging pass was with a calibrated wrench set at 25 kips. The second and third passes consisted of a 1/6 rotation of the nut for each pass. The intent was to bring the plates into visible contact.

Before each test, a Skidmore-Wilhelm bolt tension indicator verified the ability of the torque wrench to deliver the specified 12 kip or 25 kip snug. By installing a minimum of 3 fastener assemblies in the tension indicator, the torque wrench was calibrated. A spud wrench with a 4 foot pipe extension rotated the subsequent 1/3 or 1/2 turn-of -nut required. The 2” grip required a 1/3 turn of the nut rotation after the snugging pass. The 3” and 4” grips required a 1/2 turn of the nut rotation. The tests with the 6mm gap plates used only the middle to outside tightening pattern.

4.3.1.1 MIDDLE TO OUTSIDE, 12 KIP SNUG

Two tests followed the middle to the outside tightening pattern, using 6mm deformed plates applying a 12 kip snug before the turn-of-nut tightening method. CD6TN12_.MTO identifies this series of tests. The middle to outside tightening sequence is intended to follow the requirement of progressing from the most rigid part of the connection to the outside edges. Following the specified sequence, all twelve bolts received a 12 kip snug with a calibrated torque wrench. The appropriate 1/3 or 1/2 turn-of-nut concluded the tightening pass for the 2” and 3” grip tests, respectively.

4.3.1.1.1 TEST RESULTS

Tables 4.15 through 4.17 and Figures B.91 through B.100 summarize the results of the CD6TN12_.MTO series of tests. Table 4.15 indicates that the thicker the grip the lower the Average Final Snug Fastener Tension. Most of the tension was lost in the first two rows tightened.

Table 4.16 demonstrates similar results for the tightening pass. However, the tension lost in the 3” grip was very substantial, resulting in an Average Final Tight Fastener Tension of only 4.9 kips. The 12 kip snug did little to bring the plates into a “snug-tight” condition. Even another 1/2 turn-of-nut produced a low 23.3 kip Average Final Touch-up

Fastener Tension as indicated in Table 4.17. Both the 1st tightening pass and 2d tightening had Average Initial Fastener Tensions below the 41 kip requirement. Apparently, the 1/2 turn-of-nut was simply continuing to close the gap instead of applying sustainable tensions to the fasteners.

This is a clear indication of the importance of more than one snugging pass to bring the plates into firm contact before attempting the turn-of-nut tightening method. The next test with the 4" grip explores the multiple snugging pass procedure.

4.3.1.2 MIDDLE TO OUTSIDE, "CODE" SNUG

CD6TN254.MTO identifies this test. This test attempted to follow the *Bolt Specification's* criteria of having a "snug tight" condition before beginning the turn-of-nut method. The middle to the outside tightening pattern was used. The middle plate had a 6mm gap in singular curvature. Initially, a 25 kip snug was applied to the fasteners. Following this, two incremental 1/6 turn-of-nut snugging passes brought the plates into visual contact. The result of the two 1/6 turns is called the visual snug pass. The code specifies that the plates should be in firm contact. A discussion of the test results will indicate that plates in visual contact may not be in firm contact. One tightening pass of 1/2 turn-of-nut rotation followed the apparent visual "snug-tight" condition. It should be noted that all information on this test is presented in the form of three passes: the 25 kip snug pass, the visual snug pass, and the tightening pass.

4.3.1.2.1 TEST RESULTS

Tables 4.18 through Table 4.20 and Figures B.101 through B.105 summarize the results of the CD6TN254.MTO test. The first snugging pass resulted in an average final snug fastener tension of 7.5 kips. However, the first two rows tightened lost practically all

Test # For Middle to Outside Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD6TN122	5.9	4.2	11.5	2.0	8.5	2.4	3.2	2.2
CD6TN123	3.8	4.4	11.1	1.2	10.7	1.4	4.6	4.7

Note: All values in Kips

Table 4.15: Summary of fastener load results for CD6TN12_.MTO series tests - snugging pass

Test # For Middle to Outside Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD6TN122	40.2	17.5	42.0	16.2	2.9	2.1	0.9	0.2
CD6TN123	4.9	5.0	14.6	4.8	14.2	4.0	6.1	4.8

Note: All values in Kips

Table 4.16: Summary of fastener load results for CD6TN12_.MTO series tests - 1st tightening pass

Test # For Middle to Outside Pattern	Average Final Touch-up Fastener Tension	Standard Deviation	Average Initial Touch-up Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Touched-up	Standard Deviation	Average Tension Loss in Last Two Rows Touched-up	Standard Deviation
CD6TN122	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CD6TN123	23.3	17.4	31.6	16.0	14.4	2.2	2.6	3.5

Note: All values in Kips

Table 4.17: Summary of fastener load results for CD6TN12_.MTO series tests - 2d tightening pass

of the initial 25 kip snug tension applied. The second snugging pass showed improvements in the ability to sustain a snug load. However, Table 4.20 indicates that even though an

average initial tight fastener tension was 44.1 kips, there was enough tension loss to result in an average final tight fastener tension of only 35.4 kips. Six of the 12 fasteners were well below the 39 kip minimum tension. This is shown in Figure B.102.

4.3.2 CALIBRATED WRENCH INSTALLATION METHOD

Essentially, the same application of the calibrated wrench method of tightening as described in section 4.2.2 was applied for 4 more tests. The 6mm gap was the main difference from the previous tests. In an attempt to handle this increased gap, a 25 kip snugging pass was used for two of the four tests. The snugging and tightening pattern progressed from the most rigid part of the joint to the free edges (MTO). The calibrated wrench method attempted to achieve a minimum tightening pass tension of 41 kips in each bolt.

The following four tests evaluated the effect of using the set 12 kip and 25 kip tension snug pass followed by a 41 kip tightening pass. All tests included a 41 kip touch-up pass. The torque wrench was calibrated as specified in the *Bolt Specification.* Before each test, a Skidmore-Wilhelm bolt tension indicator verified the ability of the torque wrench to deliver the specified 12 kip or 25 kip snug and 41 kip tightening. The four tests used the same tightening pattern of middle to outside.

4.3.2.1 MIDDLE TO OUTSIDE, 12 KIP SNUG

Two tests followed the middle to the outside tightening pattern, using 6mm deformed plates, applying a 12 kip snug before the 41 kip tightening pass. CD6CW12_.MTO identifies this series of tests. A 41 kip touch-up pass completed each test. The tests used only the 3” and 4” grips.

Test # For Middle to Outside Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD6TN254	7.5	10.4	25.6	3.6	25.0	4.4	13.4	9.4

Note: All values in Kips

Table 4.18: Summary of fastener load results for CD6TN254.MTO test - 25k snug pass

Test # For Middle to Outside Pattern	Average Final Re-Snug Fastener Tension	Standard Deviation	Average Initial Re-Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Re-Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Re-Snugged	Standard Deviation
CD6TN254	13.0	15.2	17.5	13.2	6.4	1.9	3.0	3.2

Note: All values in Kips

Table 4.19: Summary of fastener load results for CD6TN254.MTO series tests - visual snug pass

Test # For Middle to Outside Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD6TN254	35.4	18.1	44.1	13.4	13.6	4.8	4.5	6.2

Note: All values in Kips

Table 4.20: Summary of fastener load results for CD6TN254.MTO series tests - tightening pass

4.3.2.1.1 TEST RESULTS

Table 4.21 through 4.23 and Figures B.106 through B.115 show the results of the CD6CW12_.MTO series of tests. For the snugging pass the Average Final Snug Fastener Tensions reflect the Average Initial Snug Fastener Tension. The 4" grip has an Average Final Snug Fastener Tension of about 1 kip more than the 3" grip. The Average Initial Snug Fastener Tension is also 1 kip greater for the 4" grip compared to the 3" grip. Tensions lost were essentially the same between the two grips. Most tension loss occurred in the first two rows tightened.

Tables 4.22 and 4.23 indicate that the 4" grip had an average final tight and touch-up fastener tensions that were 6 and 3 kips lower than the 3" grip. Most tension loss occurred in the first two rows tightened. Figure B.112 shows that six fasteners are below the 39 kip minimum. It would seem that the Average Final Tight Fastener Tension of 23 kips, after the tightening pass should qualify as a "snug tight" condition. However, it should be noted that Figure B.111 of Fastener Tensions shows that four of twelve fasteners are below 15 kips.

4.3.2.2 MIDDLE TO OUTSIDE, 25 KIP SNUG

Two tests followed the middle to the outside tightening pattern, using 6mm deformed plates, applying a 25 kip snug before the 41 kip tightening pass. CD6CW25_.MTO identifies this series of tests. A 41 kip touch-up pass completed each test. The tests used only the 3" and 4" grips.

Test # For Middle to Outside Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD6CW123	3.4	4.6	11.0	1.2	10.8	1.7	5.2	4.6
CD6CW124	4.5	5.2	12.1	0.9	10.8	1.5	5.3	5.4

Note: All values in Kips

Table 4.21: Summary of fastener load results for CD6CW12_.MTO series tests - snugging pass

Test # For Middle to Outside Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD6CW123	29.0	12.3	42.1	3.5	23.4	4.4	3.3	1.4
CD6CW124	23.0	15.2	42.4	3.5	30.8	6.1	9.6	6.3

Note: All values in Kips

Table 4.22: Summary of fastener load results for CD6CW12_.MTO series tests - tightening pass

Test # For Middle to Outside Pattern	Average Final Touch-up Fastener Tension	Standard Deviation	Average Initial Touch-up Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Touched-up	Standard Deviation	Average Tension Loss in Last Two Rows Touched-up	Standard Deviation
CD6CW123	42.0	3.9	42.7	3.6	1.3	0.5	0.2	0.2
CD6CW124	38.9	5.2	39.9	4.6	1.6	0.9	0.2	0.1

Note: All values in Kips

Table 4.23: Summary of fastener load results for CD6CW12_.MTO series tests - touch-up pass

4.3.2.2.1 TEST RESULTS

Tables 4.24 through 4.26 and Figures B.116 through B.125 summarize the results of the CD6CW25_.MTO series of tests. Table 4.24 shows consistent decrease in Average Final Snug Fastener Tensions as the grip thickness increased, even with the same Average Initial Snug Fastener Tensions. The average tension loss was extensive in the first two rows snugged.

Table 4.25 indicates up to code average final tight fastener tensions for the 3" grip only. The 4" grip depended on the touch-up pass to go from 36.4 kips to 41.9 kips. After the touch-up passes only one fastener in each grip was below the 39 kip minimum. There was less average tension loss in the rows after the touch-up pass. This is expected with plates in firm contact.

4.3.2.3 KIP & 25 KIP SNUG COMPARISON

The 25 kip snug produced higher average final fastener tensions for all three passes when compared to the 12 kip snug. However, only the 3" grip met the minimum requirement of 39 kip average after the first tightening pass using the 25 kip snug. Both the 3" and 4" grips using a 12 kip snug and the 4" grip using the 25 kip snug needed the touch-up pass to get close to the minimum of 39 kips. The 4" grip with the 12 kip snug actually only averaged 38.9 kips after this touch-up pass. Tension loss primarily came from the first two rows tightened. The 25 kip snug tests showed much lower tension loss during the first tightening pass when compared to the 12 kip snug tests.

4.3.3 TIGHTENING METHOD COMPARISION

Of the seven tests conducted with 6mm gap plates, four offer a comparison of the two tightening methods (turn-of-nut and calibrated wrench). CD6TN123.MTO and

Test # For Middle to Outside Pattern	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Snugged	Standard Deviation	Average Tension Loss in Last Two Rows Snugged	Standard Deviation
CD6CW253	10.0	9.9	25.2	3.9	21.3	4.1	10.8	6.3
CD6CW254	7.6	9.8	25.2	2.2	23.5	2.7	13.9	8.9

Note: All values in Kips

Table 4.24: Summary of fastener load results for CD6CW25_.MTO series tests - snugging pass

Test # For Middle to Outside Pattern	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Tightened	Standard Deviation	Average Tension Loss in Last Two Rows Tightened	Standard Deviation
CD6CW253	40.9	3.5	42.3	2.5	2.7	2.1	0.4	0.2
CD6CW254	36.4	5.7	42.4	2.0	10.8	4.1	2.0	1.6

Note: All values in Kips

Table 4.25: Summary of fastener load results for CD6CW25_.MTO series tests - tightening pass

Test # For Middle to Outside Pattern	Average Final Touch-up Fastener Tension	Standard Deviation	Average Initial Touch-up Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Touched-up	Standard Deviation	Average Tension Loss in Last Two Rows Touched-up	Standard Deviation
CD6CW253	43.6	2.9	43.9	2.9	0.4	0.1	0.3	0.2
CD6CW254	41.9	2.4	42.2	2.3	0.6	0.2	0.1	0.0

Note: All values in Kips

Table 4.26: Summary of fastener load results for CD6CW25_.MTO series tests - touch-up pass

CD6CW123.MTO have all the same conditions except for the method of tightening. Also,

CD6TN254.MTO and CD6CW254.MTO will be compared. All tests included touch-up passes.

For the 3" grip with 12 kip snug, the average snug tensions and tension losses are the same, as expected. However, the tightening pass shows a definite difference in values. The Average Final Tight Fastener Tension for the turn-of-nut method is well below the value for the calibrated wrench method. The Average Initial Tight Tension of 14.6 kips is well below the 42.1 kips of the calibrated wrench method. This indicates that the "snug tight" condition is critical to the turn-of-nut method. This concept is reinforced in the touch-up pass also.

The 25 kip snug tests indicate the same results. Even though 25 kips were used to snug, the turn-of-nut method never achieves an average final touch-up fastener tension over 39 kips. This might be interpreted as a benefit in using the calibrated wrench method for the larger deformed plates.

4.4 PLATE DEFORMATION COMPARISON

The 3mm gap tests seem to support the turn-of-nut method and perhaps the middle to outside tightening pattern for at least the thicker grip of 4". All average final tight fastener tensions were greater for the turn-of-nut method.

The 6mm gap tests support the calibrated wrench method over the turn-of-nut method. However, the reason is due to the ambiguity in obtaining a "snug-tight" condition. While the calibrated wrench method guarantees average initial tight fastener tensions of about 41 kips, the turn-of-nut offers no such guarantee if the plates are not in firm contact. The 6mm gap clearly exposes the need for firm plate contact. A single snug pass or even the appearance of "snug tight" does not qualify as firm contact.

5. CHAPTER 5
CONNECTION TESTS WITH HUCK C50L FASTENERS

5.1 GENERAL

The final 4 tests consisted of Huck International C50L lock-pin and collar fasteners. The tests evaluated the same grip lengths as the previous tests that used conventional fasteners. The Huck fasteners were also 7/8" in diameter (part #C50LFR-DBR28) and of three lengths. The fasteners had grip numbers 28, 44, and 60 corresponding to the 2", 3", and 4" length grips. All lock-pins were mechanically galvanized. Non-galvanized collars secured the lock-pins to form the connection.

Twelve fasteners connected three plates of ASTM A572 Grade 50 steel, producing a slip-critical lap splice connection. Three connection grips were evaluated. Figure 5.1 identifies the three fastener lengths and their respective connection (grip) grips. Referring back to Figure 4.2 reiterates the dimensions of the connection and the numbered rows of fasteners.

Grip Number	Total Grip (inches)	Thickness of Interior Plate (inches)	Thickness of Exterior Plates (inches)
28	2	1	1/2
44	3	1-1/2	3/4
60	4	2	1

Figure 5.1: Fastener Lengths and Grip Thickness

All tests involved a deformed interior plate. As described in Chapter 2, the single curvature interior plate produced a 3mm or 6mm gap between itself and the top exterior plate. This out-of-flatness is well within the maximum gap (9.5mm) that the ASTM A6 specification allows for milled steel plates.

The three primary components of a test set-up were the same as for the conventional fastener tests. C-clamps and steel blocks braced the connection against movement during fastener installation. Only the force of the tensioned fasteners influenced the joining of the plates. Each lock-pin in the connection had a BTM strain gauge epoxied within the core of the unthreaded shank. Throughout the installation sequence strain readings were constantly recorded with the data acquisition system for future computation of fastener tensions.

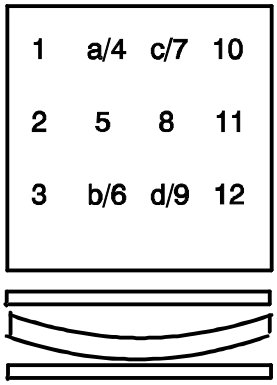
The presentation of fastener tensions (test results) follows the same general format as for the conventional fastener tests conducted. The primary difference is that only one pass of fastener tightening was conducted. Therefore, there is only one table for each series of tests. For the Huck fasteners, one pass means that installation did not involve any partial swaging of the collar. However, three tests incorporated a temporary snugging of the plates using "snug-up" conventional fasteners before lock-pin and collar fasteners were installed. The forth test had no snugging of the plates prior to complete lock-pin and collar installation.

For each series of tests, the one summary table indicates the same final four statistics as calculated for the conventional fastener tests. Of the four statistics, the first indicates the Average Final Fastener Tension. This is the average tension that existed in all twelve fasteners upon completion of installation pass. The second statistic identifies the average initial tension experienced by each fastener right after it was installed. The third and forth statistics show the average loss in tension between the initial installation tension in each fastener and the final tension upon installing all twelve fasteners. Specifically, the third statistic is an average tension loss experienced by the first two rows installed. These first two rows were always the two interior rows for these tests. The forth statistic is the average tension loss experienced by the last two rows installed. The last two rows were the exterior rows. All four statistics have their respective standard deviations indicated.

In Appendix C, five figures for each test present fastener by fastener tensions. The first figure shows the complete history of all fastener tensions throughout the sequence of installation. The second figure is a bar chart of final tensions for each fastener at the end of the test. The remaining three figures graphically show all the tensions experienced by three selected fasteners. This tensile load history of a fastener is plotted throughout the

installation of all fasteners. The first fastener installed is always one of the three bolts graphically represented. Fasteners #8 and #2 are the other two fasteners plotted, as per all the other middle to outside tightening pattern tests.

Figure 5.2 illustrates the numbering template used for all tests. For the three tests involving the 4 conventional fastener snug, the letters a, b, c, and d indicate the four bolts used to bring the plates together in an attempted snug-tight condition. The one test that involved no snugging uses the same numbering template, excluding the letters a,b,c, and d. The pattern of installation for all tests follows the middle to outside sequence, going from the most rigid part to the connection to the free edges. The fastener numbers underlined and in bold print indicate the fasteners that are graphically presented in the tensile load history figures.



Numbering Template

Installation Pattern	Sequence of Installation
Conventional Fasteners for Snug	a, b, c, d
Huck Fasteners (* = removal of Conventional Fasteners)	5, a*, **4**, b*, 6, c*, 7, **8**, d*,9, 1,**2**,3,10,11,12

Figure 5.2: Fastener Numbering Template Installation Sequences

The same six variables identify each of the specific tests. These variables indicate the type of fastener, the amount of plate deformation, the tightening method used, the amount of snugging applied before tightening, the grip thickness of the connection, and the pattern used in tightening. For the four tests conducted with Huck fasteners, the eleven digit syntax is defined below:

1st Digit: Type of fastener

C: Conventional fasteners (for all tests in Chapter 4)

H: Huck C50L fasteners (for all tests in this chapter)

2nd Digit: Plate condition

D: Deformed interior plate (for all tests)

F: Flat plates

3rd Digit: Middle gap created by single curvature interior plate before loading

3: 3mm gap between bent interior plate and top flat plate (for three tests)

6: 6mm gap between bent interior plate and top flat plate (for one test)

4th & 5th Digits: Method of Installation

CW: Calibrated Wrench method

TN: Turn-of-Nut method

NS: No snug (for one test in this chapter)

CS: Snug with 4 conventional fasteners before installing Huck fasteners

6th & 7th Digits: Snug tension applied before tightening method

12: 12 kip tension

25: 25 kip tension

41: 41 kip tension

8th Digit: Grip thickness of connection

2: 2 inch grip

3: 3 inch grip

4: 4 inch grip

9th - 11th Digits: Pattern of Tightening

MTO: Middle to Outside (all tests in this chapter)

LTR: Left to Right

OTM: Outside to Middle

For example, the label of the first test is HD3CS412.MTO. This describes a Huck fastener test with deformed plates (3mm). The method of installing the fasteners was with a single pass after a plate snug using 4 conventional fasteners at 41 kips. The thickness of the grip was 2 inches (consisting of the 1 inch interior plate and the 1/2 inch thick exterior plates). The pattern of tightening was from the middle fasteners to the outside fasteners.

5.2 3MM DEFORMED PLATES

Three tests involved the use of 3mm deformed plates. Prior to fastener installation, the 3mm gap existed between the bent interior plate and the flat exterior plate on top. Four conventional fasteners with 41 kips of tension brought the plates together before the installation of the Huck fasteners, as seen in Figure 5.3. The tests evaluated each of the three grip lengths. All three tests used the middle to outside tightening pattern.

5.2.1 SINGLE PASS INSTALLATION METHOD, WITH CONVENTIONAL BOLT SNUG

As noted by Riggleman, deformed plates present a significant challenge to the lock-pin and collar fastener. Partial swaging of the collar, in an attempt to produce a “snug-tight” condition in the plates, introduces a limit on the fastener's ability to close the gap upon further swaging. Once the first few grooves of a collar are swaged, subsequent full swaging must begin at the point of initial swaging. Swaging can only extend the finite length of the collar. A gap may still exist after full swaging. The values of Average Final Tight Tension for Riggleman's tests with partial swage snugging were 34.6 kips, 37.9 kips, and 33.1 kips for the 2", 3", and 4" grips. It represented a slight improvement over the tests that involved no snugging (38.9 kips, 32.5 kips, and 31.5 kips).

In an effort to follow the *Bolt Specification*, the four conventional fasteners with 41 kips of tension required a few passes with a torque wrench to bring the plates into firm contact. Before each test, a Skidmore-Wilhelm bolt tension indicator verified the ability of the torque wrench to deliver the specified 41 kip snug. During the snugging process, tensions were monitored to indicate the need for subsequent passes. However, without a monitoring device a few passes with a calibrated wrench will ensure a 41 kip tension in all bolts. Once all four conventional fasteners had 41 kips of tension, the Huck fasteners were installed. The intent was to avoid beginning the swaging process until a "snug-tight" condition existed. Figure 5.3 shows the first Huck fastener just before swaging.

The following three tests evaluated the effectiveness of using the 4 conventional bolt snug. Huck fasteners systematically filled the open holes or replaced the conventional fasteners one at a time using one pass of complete swaging. The *Bolt Specification* requires the same initial minimum tension of 41 kips in each fastener. This initial tension is 5%

greater than the minimum tension of 39 kips required of all fasteners in the connection after the completion of the installation pass. The sequence of installation is described above in Figure 5.2.

5.2.1.1 TEST RESULTS

Table 5.1 and Figures C.1 through C.15 summarize the results of the HD3CS41_.MTO series of tests. Table 5.1 shows a decrease in Average Final Fastener Tension as the grip thickness increased. Only the 2" grip test sustained an average tension above the 39 kip minimum. Most tension loss occurred in the first two rows of fasteners installed for all the tests. The Average Initial Fastener Tensions for the 2" and 3" grips are slightly lower for than the required 41 kips.

Figure C.1 of test HD3CS412.MTO shows that the fasteners maintained their initial installation tension fairly well. The two out of three fasteners that did not finish the test with tensions above 39 kips had low initial tensions to begin with. For all three tests, as the conventional fastener #c was removed, the most recently installed Huck fastener #6 tended to loss up to 1 kip of tension. As the other conventional fasteners were removed, most Huck fasteners did not change tension. It is possible that the installation of fastener #8 prior to the removal of #c would have kept tensions more consistent in fastener #6.

Figures C.7 and C.12 of the 3” and 4" grips indicate fasteners that fell well below 39 kips despite initial tensions above 41 kips. The HD3CS413.MTO test had 7 fasteners below the 39 kip minimum, five of which had initial tensions above 39 kips (but all below the 41 kip minimum). The HD3CS414.MTO test had ten fasteners fall below 39 kips by the end of the test. Seven of the ten initially had tensions above 41 kips.

Figure 5.3: Four conventional fasteners (41 kips of tension) before installation of Huck fasteners

5.2.2 TIGHTENING METHOD COMPARISON

Nine tests are available for comparison between the three tightening methods for Huck fasteners. The results of Riggleman's two tightening methods (six tests) and the tightening method used for the previous three tests are presented in Table 5.1. The tests involved all three grip lengths. All tests used the 3mm deformed plates, and followed the same middle to outside installation principle. When using the 4 conventional fasteners for snugging, the first two fasteners (#4 and #5) were installed in reverse order to maintain at

least 4 fasteners in the connection before removing the conventional fasteners. This was the only difference in the installation sequence among the nine tests.

The "snug-tight" condition that existed before fastener collars were fully swaged is the primary difference between the three tightening methods involved. Riggleman evaluated the no snug condition and the partial snug condition using three tests for each. The no snug tests (HDNS-_) consisted of full installation of each fastener using only one pass. For the tests with snug (HDS-_), partially swaged collars induced a target tension of 12 kips in the fasteners. After a complete snugging pass, a tightening pass completely swaged the collars and break-necks fractured inducing a target tension of 41 kips. The last three tests (HD3CS41_.MTO), with the 4 conventional bolts for a snug-tight condition, involved full installation of each Huck fastener using only one pass, collars fully swaged and break-necks fractured.

	No Snug (HDNS-_)	12 kip Snug Using Partial Swaging of Huck Fasteners (HDS-_)	41 kip snug Using 4 Conventional Fasteners (HD3CS41_.MTO)
2" grip	38.9	34.6	39.5
3" grip	32.5	37.9	37.4
4" grip	31.5	33.1	36.2

Note: All values in Kips

Table 5.1: Average Final Fastener Tension for Huck fasteners, 3mm deformed plates

The HD3CS41_.MTO tests show a slight trend towards achieving the target Average Final Fastener Tension of 39 kips. However, only the 2" grip test ends with a average above 39 kips. In order to ensure a fair comparison, the Table 5.2 shows the Average Initial Tensions for each test. This is the average of the initial tension experienced by each fastener right after it was installed.

	No Snug	12 kip Snug Using Partial Swaging	41 kip snug Using 4 Conventional

	(HDNS-_)	of Huck Fasteners (HDS-_)	Fasteners (HD3CS41_.MTO)
2" grip	39.2	36.4	40.1
3" grip	39.6	38.7	40.1
4" grip	42.5	41.0	41.5

Note: All values in Kips

Table 5.2: Average Initial Fastener Tension for Huck fasteners, 3mm deformed plates

These values indicate that regardless of the initial tension that each fastener had upon installation, the grip thickness and the amount of snug prior to installation are controlling factors in the Average Final Fastener Tensions. The method of using 4 conventional fasteners for "snug-tight" condition seems to provide higher Average Final Tight Fastener Tensions. However, as stated earlier, this method is still not effective for the 3" and 4" grip tests.

5.3 6MM DEFORMED PLATES

One Huck fastener test involved the use of 6mm deformed plates. Prior to fastener installation, the 6mm gap existed between the bent interior plate and the flat exterior plate on top. The method of fastener installation involved full swaging using only one pass. This test used the 2" grip thickness. The intent was to evaluate the effect of the larger deformation on a grip that seemed to be averaging fairly well with the other tightening methods.

5.3.1 SINGLE PASS INSTALLATION METHOD, NO SNUG

This one test followed the middle to the outside tightening pattern, using 6mm deformed plates, with a one pass complete installation without any snug. HD6NS--2.MTO identifies this series of tests. The middle to outside tightening sequence is intended to follow the requirement of progressing from the most rigid part of the connection to the outside edges. Following the specified sequence as in Figure 4.4, all twelve fasteners joined the plates in the connection.

5.3.1.1 TEST RESULTS

Table 5.3 and Figures C.16 through C.20 show the results of this test. The Average Final Fastener Tension was below 39 kips despite the 40.3 kip average for initial fastener tension. Significant loss of tension occurred in the first two rows installed. Eleven of the twelve fasteners installed fell below the 39 kip minimum for final fastener tension by the end of the test. The lowest final fastener tension was that of fastener #7 at 22.4 kips.

5.3.2 PLATE DEFORMATION COMPARISON

Four other 2" grip tests provide the basis for comparison of the HD6NS--2.MTO test results. Riggleman performed three of these tests. The first test (HFNS-2) involved no plate deformation and no snugging, simply a single full swage pass. The second test (HDNS-2) used 3mm deformed plates and no snugging, also using only a full swage pass. The third test (HDS-2) used partial swaging for an initial 12 kip snug pass followed by a full swaging pass. The fourth test (HD3CS412) used only a full swage pass after 4 conventional bolts provided an initial snug-tight condition. The four statistics for all five tests are presented in Table 5.3.

Test # All Middle to Outside Pattern	Average Final Fastener Tension	Standard Deviation	Average Initial Fastener Tension	Standard Deviation	Average Tension Loss in 1st Two Rows Installed	Standard Deviation	Average Tension Loss in Last Two Rows Installed	Standard Deviation
HFNS-2	38.4	0.8	38.4	0.7	0.4 (GAIN)	0.3	0.3	0.3
HDNS-2	38.9	1.6	39.2	1.7	0.5	0.7	0.0	0.2
HDS-2	34.6 full swage	1.5	36.4 full swage	1.7	2.7	0.6	1.2	0.3

HD3CS412	39.5	1.0	40.1	1.0	0.8	0.3	0.4	0.3
HD6NS--2	36.6	5.2	40.3	2.4	7.2	3.7	0.4	0.5

Note: All values in Kips

Table 5.3: Summary of all 2" Grip Huck Fastener Tests

Only the tightening method used in HD3CS412 meets the requirements of the *Bolt Specification.* However, this method becomes less effective as the grip length increases, as discussed in section 5.2.2. For the 2" grip, the single pass method begins to loose its effectiveness for meeting the required 39 kip minimum tension as the gap increases. There seems to be clear evidence that the snug-tight condition of the *Bolt Specification* is a critical requirement for obtaining the final 39 kip minimum tension in fasteners.

6. CHAPTER 6

OVERALL SUMMARY AND CONLUSIONS

Four primary factors (the method of installation, the pattern of tightening, the thickness and out-of-flat condition of the connected material, and the degree of "snug tight" existing between the material before final tightening) provide a basis for an evaluation of the installation characteristics of high strength fasteners. Table 6.1 through Table 6.6 summarize the results of all tests in the form of average initial and final tensions for the snugging, tightening, and touch-up passes. The turn-of-nut and calibrated wrench methods of installation represent the majority of tests.

For 3mm deformed plates, the turn-of-nut method of installation provided a more consistent level of acceptable final fastener tension after the tightening pass. 9 tests used the turn-of-nut method of installation with 3mm deformed plates. All tests averaged final fastener tensions above 39 kips. The 9 tests using the calibrated wrench method of installation averaged only 7 tests above 39 kips. The 3 alternative design fastener test had 1 of 3 tests that averaged above 39 kips.

For 6mm deformed plates, the calibrated wrench method of installation provided consistently higher final fastener tensions after the tightening pass. The average of the 4 calibrated wrench tests was 32.3 kips compared to an average of 19.4 kips for the 3 turn-of-nut tests. Both averages are after the tightening pass. The one alternative design test averaged only 36.6 kips.

The three patterns of tightening were middle to outside, left to right, and outside to middle. 6 tests of each pattern (3mm gap) provide a comparison of the three patterns. The Middle to outside produces an almost 3 kip higher average final fastener tension after the tightening pass. It should be noted that if only the 2" and 3" grip test results are considered, there is only a difference of about 1 kip between the tightening patterns. However, when 4" grip tests are compared, the middle to outside tightening pattern produced the higher final fastener tensions.

The greater the thickness of the plates and the more the initial curvature of the center plate, the lower the final average fastener tensions after the tightening pass. It is noted that the calibrated wrench method of installation provides more dependable average final fastener tensions for these cases.

A comparison of the data in Appendix A and Appendix B reveals two important points. A turn of nut of 1/2 of a rotation moves the nut 0.053" for a 7/8" diameter bolt (ignoring any elongation of the bolt). Almost all 3mm gap tests had gaps less than 0.05" after the snugging pass. All tests had average final tight fastener tensions greater than 39 kips. The 6mm gap tests that resulted well below 39 kip averages had gaps greater than 0.05" after the snugging pass.

The second point is a suggestion on how to ensure the turn-of-nut method meets the requirement of the code. For plate deformations creating gaps greater than 3mm the turn-of-nut method should be checked after the tightening pass. A suggestion would be to check at

least the first few fasteners tightened (most likely to be loose) with a calibrated torque wrench.

A 12 kip "snug tight" condition was used for 19 of the 29 tests. This proved fairly satisfactory until plate deformations of 6mm were encountered. The turn-of-nut method of installation, which relies heavily upon a snug tight condition, failed to meet the minimum of 39 kips final fastener tension. The calibrated wrench method a touch-up pass, as required in the *Bolt Specification*, provided the most consistent final fastener tensions of at least 39 kips.

Install. Method	Average Initial Snug Tension	Average Final Snug Tension	Average Initial "Tight" Tension	Average Final "Tight" Tension	Average Initial Touch-up Tension	Average Final Touch-up Tension
Turn-of-Nut 12 kip Snug MTO	9.6	7.1	52.8	51.9	N/A	N/A
Turn-of-Nut 12 kip Snug LTR	11.9	8.7	53.2	52.1	N/A	N/A
Turn-of-Nut 12 kip Snug OTM	11.1	7.7	52.6	51.8	N/A	N/A

Calibrated Wrench 25 kip Snug MTO	24.3	22.6	41.4	40.9	42.6	42.3
Calibrated Wrench 12 kip Snug LTR	12.5	8.9	40.6	39.9	41.7	41.6
Calibrated Wrench 12 kip Snug OTM	11.6	8.6	41.4	40.9	N/A	N/A
Huck C50L 4 Bolt Snug MTO	N/A	N/A	40.1	39.5	N/A	N/A

Note: All Values in Kips
MTO = Middle to Outside Tightening Pattern
LTR = Left to Right Tightening Pattern
OTM = Outside to Middle Tightening Pattern

Table 6.1: Summary of fastener tensions - 2" grip, 3mm deformed plate tests

Install. Method	Average Initial Snug Tension	Average Final Snug Tension	Average Initial "Tight" Tension	Average Final "Tight" Tension	Average Initial Touch-up Tension	Average Final Touch-up Tension
Turn-of-Nut 12 kip Snug MTO	12.8	5.7	55.8	54.2	N/A	N/A
Turn-of-Nut 12 kip Snug LTR	11.7	4.1	56.6	55.0	N/A	N/A
Turn-of-Nut 12 kip Snug OTM	11.6	4.7	54.4	53.2	N/A	N/A

Calibrated Wrench 25 kip Snug MTO	26.2	18.9	41.5	41.0	40.2	40.2
Calibrated Wrench 12 kip Snug LTR	11.3	4.1	43.7	41.7	43.2	43.2
Calibrated Wrench 12 kip Snug OTM	11.8	5.4	40.9	39.9	N/A	N/A
Huck C50L 4 Bolt Snug MTO	N/A	N/A	40.1	37.4	N/A	N/A

Note: All Values in Kips
MTO = Middle to Outside Tightening Pattern
LTR = Left to Right Tightening Pattern
OTM = Outside to Middle Tightening Pattern

Table 6.2: Summary of fastener tensions - 3" grip, 3mm deformed plate tests

Install. Method	Average Initial Snug Tension	Average Final Snug Tension	Average Initial "Tight" Tension	Average Final "Tight" Tension	Average Initial Touch-up Tension	Average Final Touch-up Tension
Turn-of-Nut 12 kip Snug MTO	13.5	5.1	53.1	50.0	N/A	N/A
Turn-of-Nut 12 kip Snug LTR	11.6	4.0	48.9	42.1	N/A	N/A
Turn-of-Nut 12 kip Snug OTM	11.7	4.4	46.2	39.5	N/A	N/A
Calibrated						

Wrench 25 kip Snug MTO	25.0	11.0	42.7	40.8	41.5	41.3
Calibrated Wrench 12 kip Snug LTR	11.8	4.5	41.6	31.4	40.4	40.1
Calibrated Wrench 12 kip Snug OTM	12.4	4.4	42.6	37.0	N/A	N/A
Huck C50L 4 Bolt Snug MTO	N/A	N/A	41.5	36.2	N/A	N/A

Note: All Values in Kips
MTO = Middle to Outside Tightening Pattern
LTR = Left to Right Tightening Pattern
OTM = Outside to Middle Tightening Pattern

Table 6.3: Summary of fastener tensions - 4" grip, 3mm deformed plate tests

Install. Method	Average Initial Snug Tension	Average Final Snug Tension	Average Initial "Tight" Tension	Average Final "Tight" Tension	Average Initial Touch-up Tension	Average Final Touch-up Tension
Turn-of-Nut 12 kip Snug MTO	11.5	5.9	42.0	40.2	N/A	N/A
Huck C50L No Snug MTO	N/A	N/A	40.3	36.6	N/A	N/A

Note: All Values in Kips, MTO = Middle to Outside Tightening Pattern

Table 6.4: Summary of fastener tensions - 2" grip, 6mm deformed plate tests

			Average	Average	Average	Average

Install. Method	Average Initial Snug Tension	Average Final Snug Tension	Initial "Tight" Tension	Final "Tight" Tension	Initial Touch-up Tension	Final Touch-up Tension
Turn-of-Nut 12 kip Snug MTO	11.1	3.8	14.6	4.9	31.6	23.3
Calibrated Wrench 12 kip Snug MTO	11.0	3.4	42.1	29.0	42.7	42.0
Calibrated Wrench 25 kip Snug MTO	25.2	10.0	42.3	40.9	43.9	43.6

Note: All Values in Kips, MTO = Middle to Outside Tightening Pattern

Table 6.5: Summary of fastener tensions - 3" grip, 6mm deformed plate tests

Install. Method	Average Initial Snug Tension	Average Final Snug Tension	Average Initial "Tight" Tension	Average Final "Tight" Tension	Average Initial Touch-up Tension	Average Final Touch-up Tension
Turn-of-Nut 25 kip Snug then Code Snug MTO	25.6	7.5	17.5	13.0	44.1	35.4
Calibrated Wrench 12 kip Snug MTO	12.1	4.5	42.4	23.0	39.9	38.9
Calibrated Wrench 25 kip Snug	25.2	7.6	42.4	36.4	42.2	41.9

MTO						

Note: All Values in Kips, MTO = Middle to Outside Tightening Pattern

Table 6.6: Summary of fastener tensions - 4” grip, 6mm deformed plate tests

APPENDIX A

GAP HISTORIES FOR ALL TESTS

INDEX OF FIGURES
95

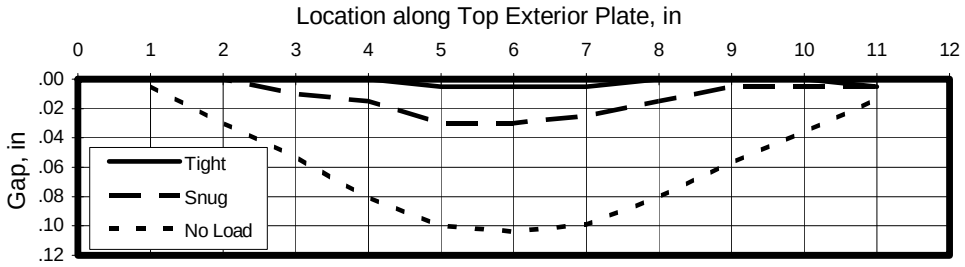


Figure A.1: Front Gap Between Interior Plate and Top Exterior Plate CD3TN123.MTO

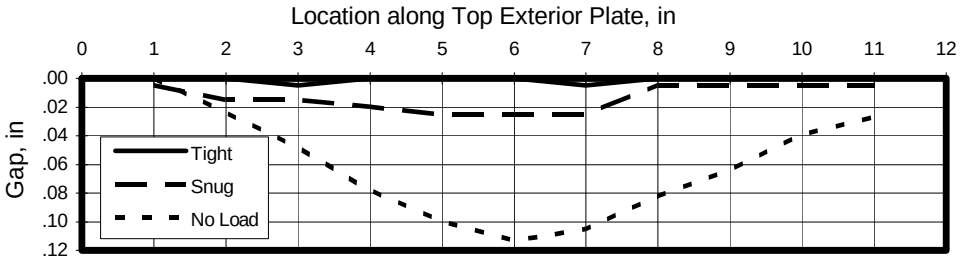


Figure A.2: Back Gap Between Interior Plate and Top Exterior Plate CD3TN123.MTO

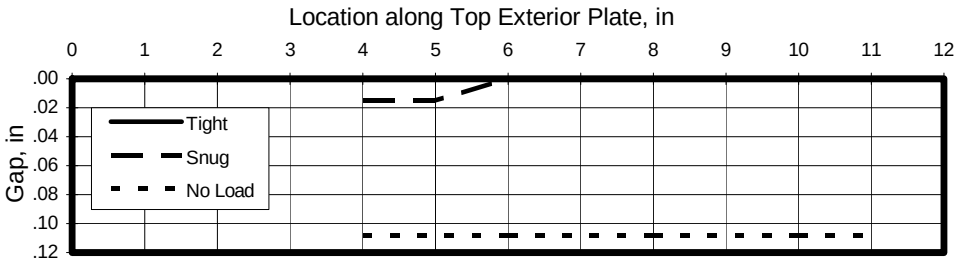


Figure A.3: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN123.MTO

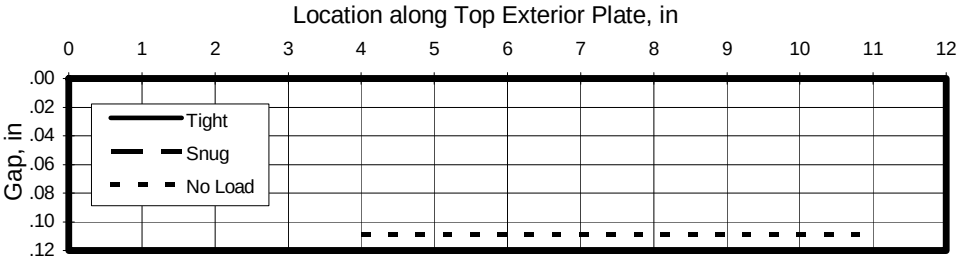


Figure A.4: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN123.MTO

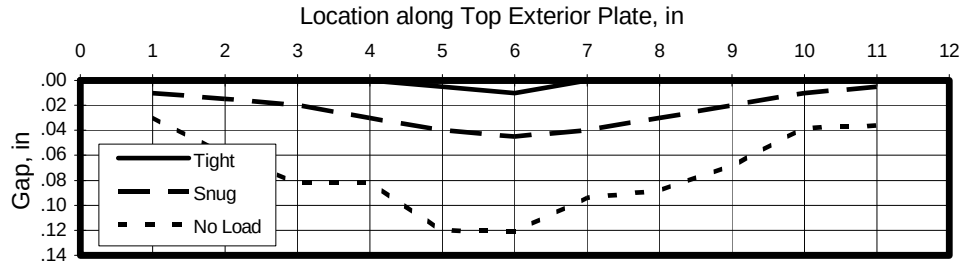


Figure A.5: Front Gap Between Interior Plate and Top Exterior Plate CD3TN124.MTO

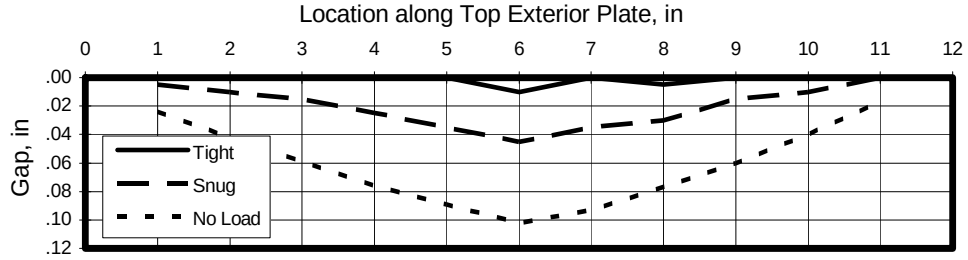


Figure A.6: Back Gap Between Interior Plate and Top Exterior Plate CD3TN124.MTO

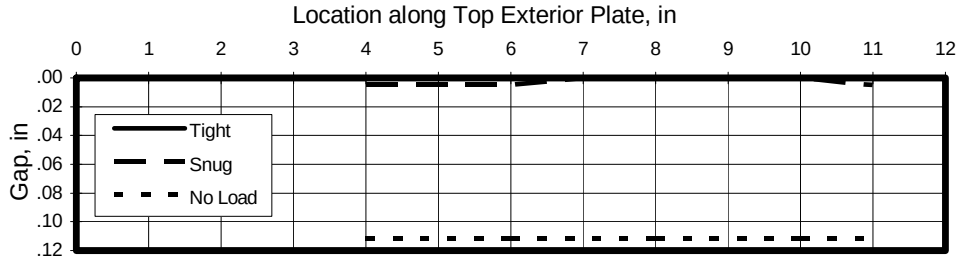


Figure A.7: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN124.MTO

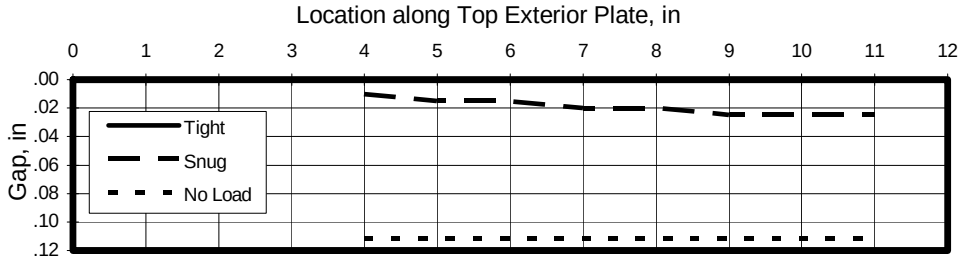


Figure A.8: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN124.MTO

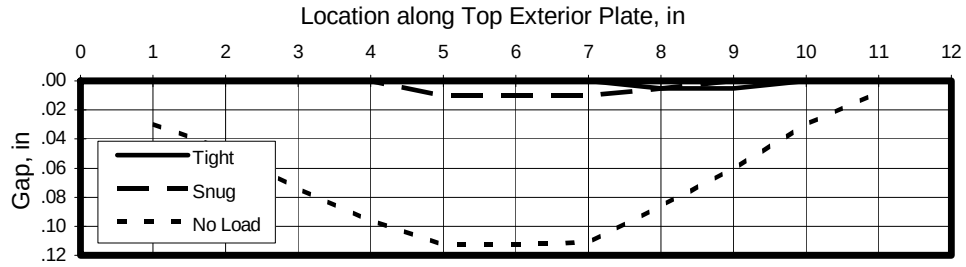


Figure A.9: Front Gap Between Interior Plate and Top Exterior Plate CD3TN122.LTR

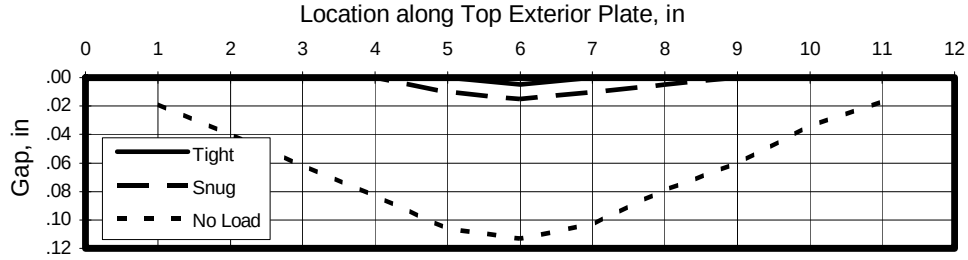


Figure A.10: Back Gap Between Interior Plate and Top Exterior Plate CD3TN122.LTR

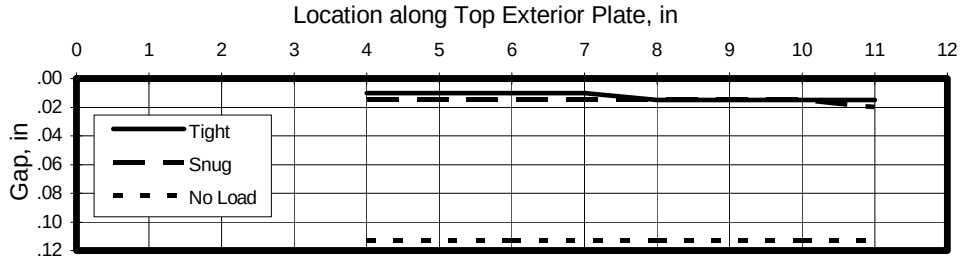


Figure A.11: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN122.LTR

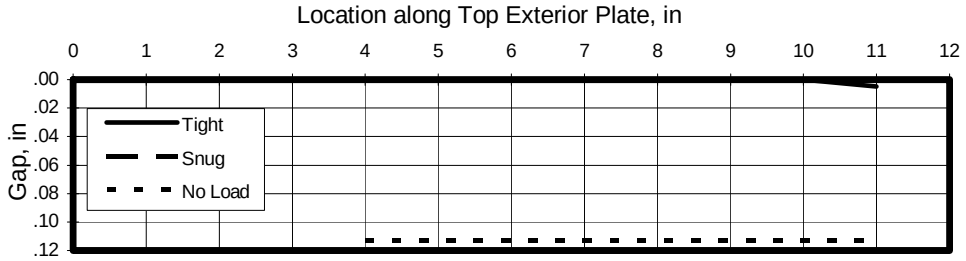


Figure A.12: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN122.LTR

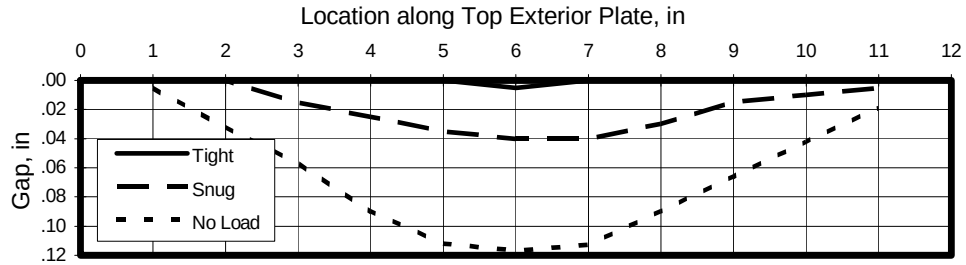


Figure A.13: Front Gap Between Interior Plate and Top Exterior Plate CD3TN123.LTR

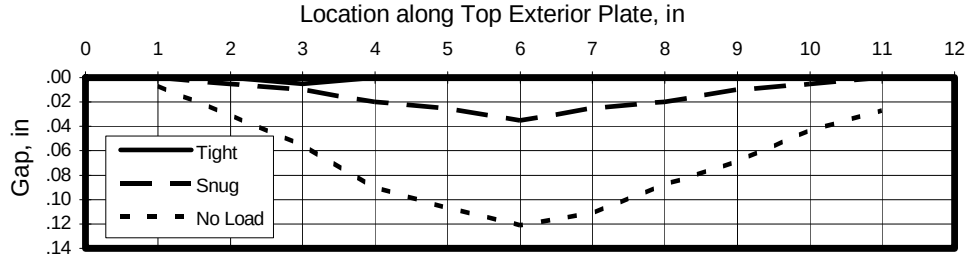


Figure A.14: Back Gap Between Interior Plate and Top Exterior Plate CD3TN123.LTR

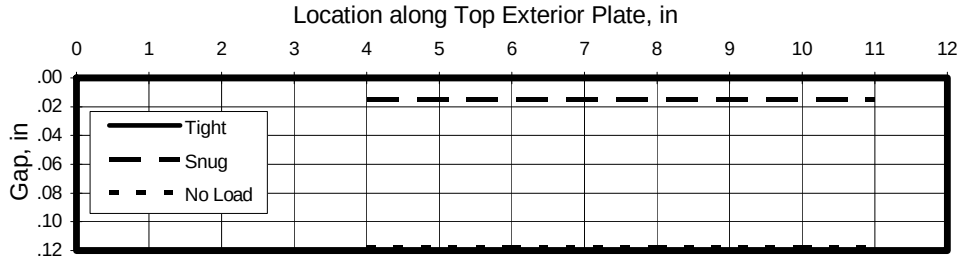


Figure A.15: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN123.LTR

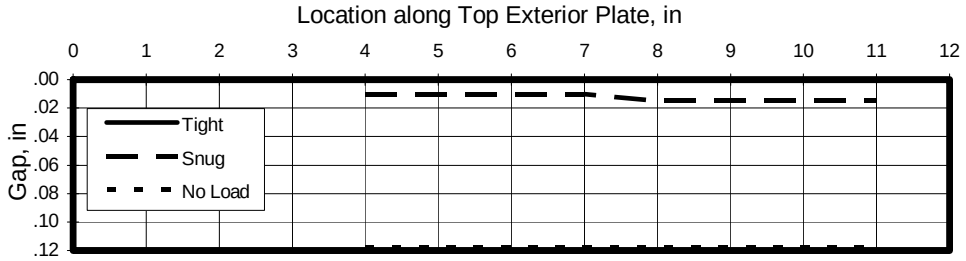


Figure A.16: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN123.LTR

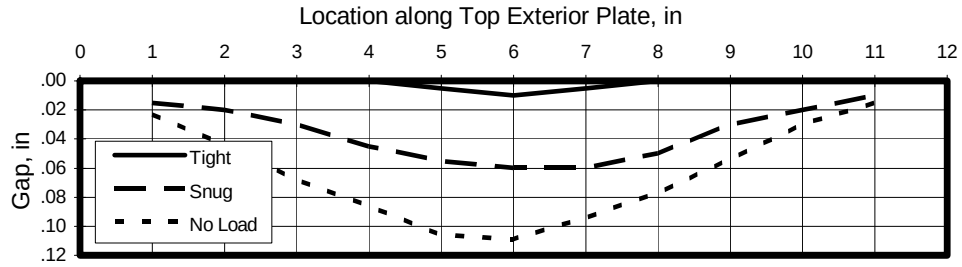


Figure A.17: Front Gap Between Interior Plate and Top Exterior Plate CD3TN124.LTR

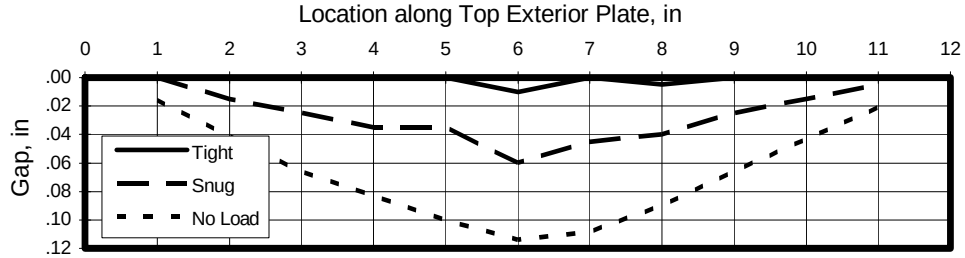


Figure A.18: Back Gap Between Interior Plate and Top Exterior Plate CD3TN124.LTR

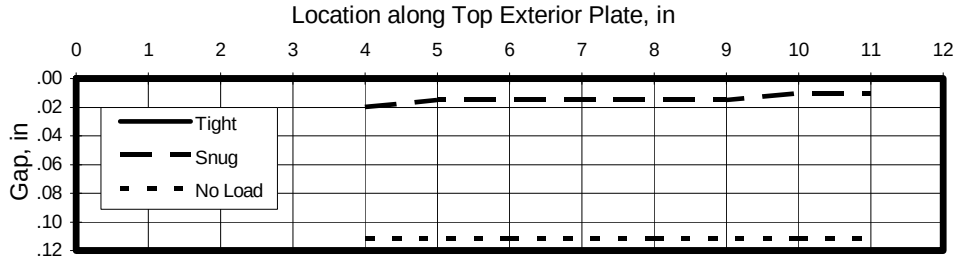


Figure A-19: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN124.LTR

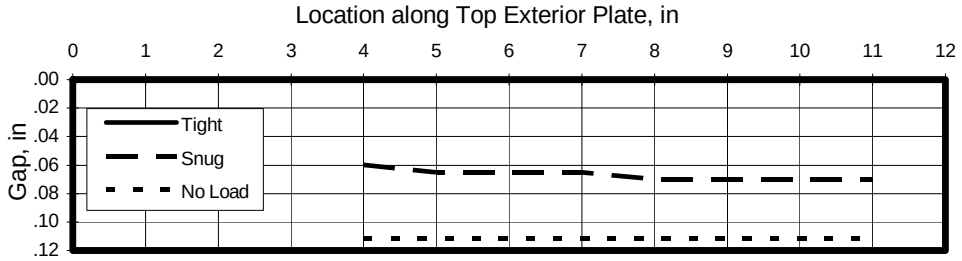


Figure A.20: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN124.LTR

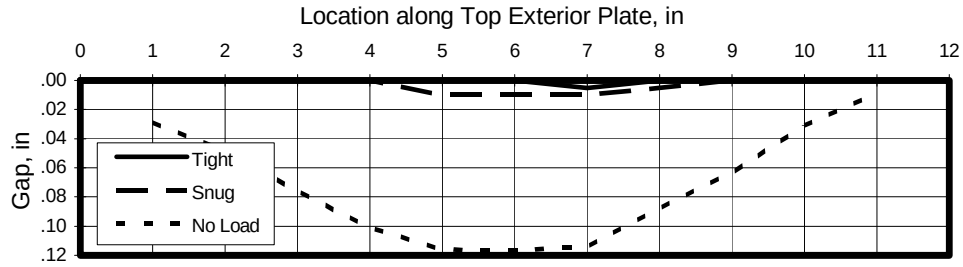


Figure A.21: Front Gap Between Interior Plate and Top Exterior Plate CD3TN122.OTM

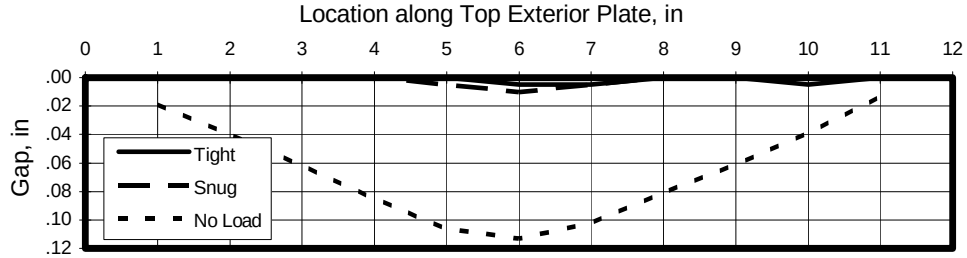


Figure A.22: Back Gap Between Interior Plate and Top Exterior Plate CD3TN122.OTM

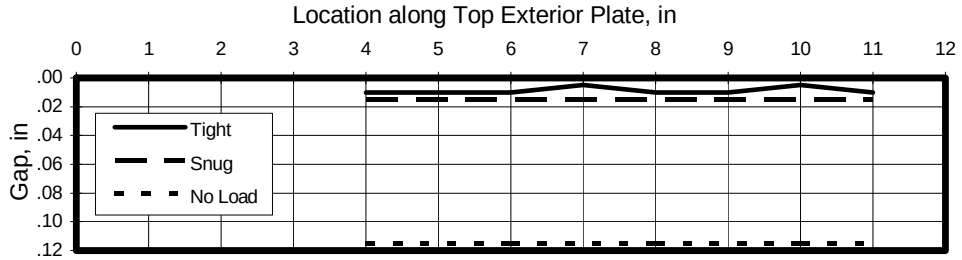


Figure A.23: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN122.OTM

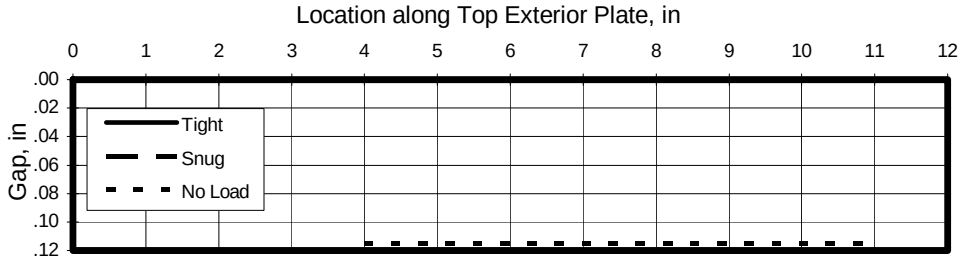


Figure A.24: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN122.OTM

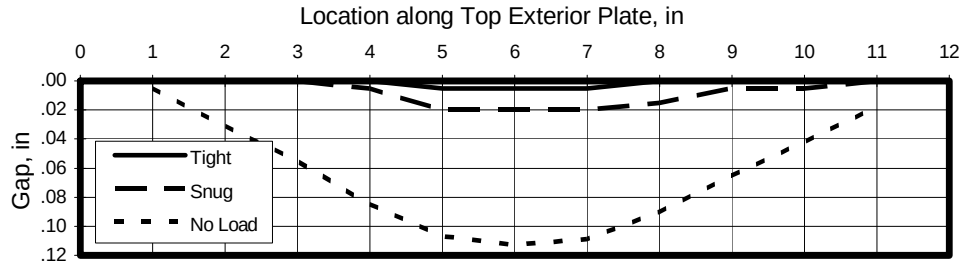


Figure A.25: Front Gap Between Interior Plate and Top Exterior Plate CD3TN123.OTM

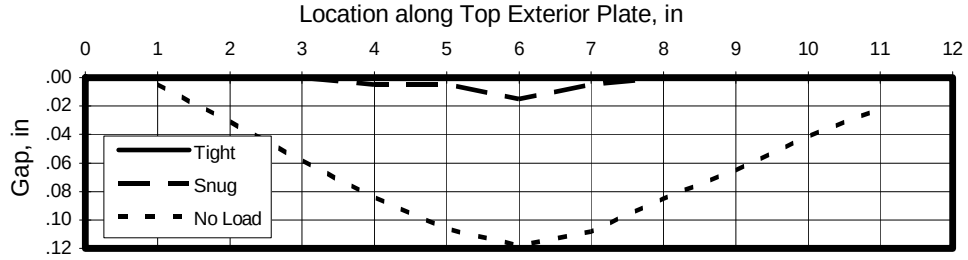


Figure A.26: Back Gap Between Interior Plate and Top Exterior Plate CD3TN123.OTM

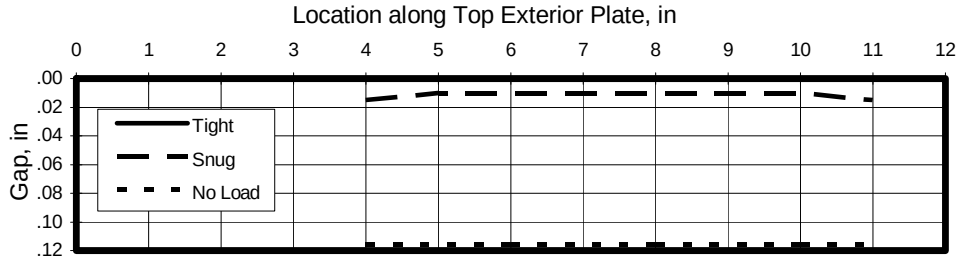


Figure A.27: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN123.OTM

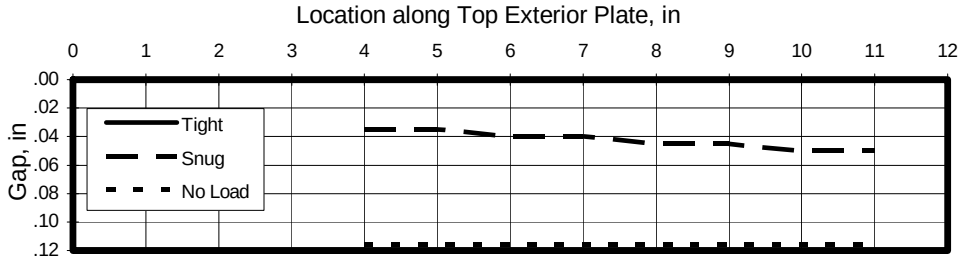


Figure A.28: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN123.OTM

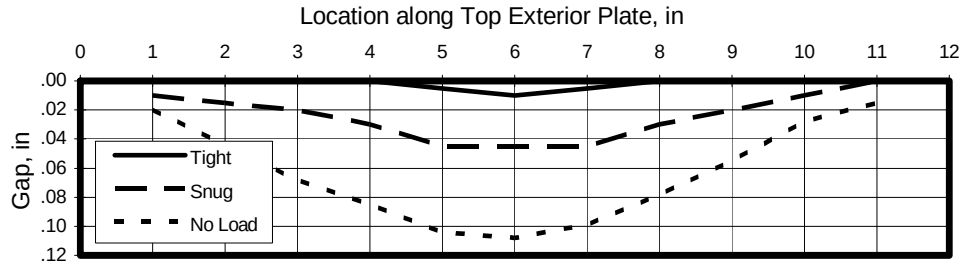


Figure A.29: Front Gap Between Interior Plate and Top Exterior Plate CD3TN124.OTM

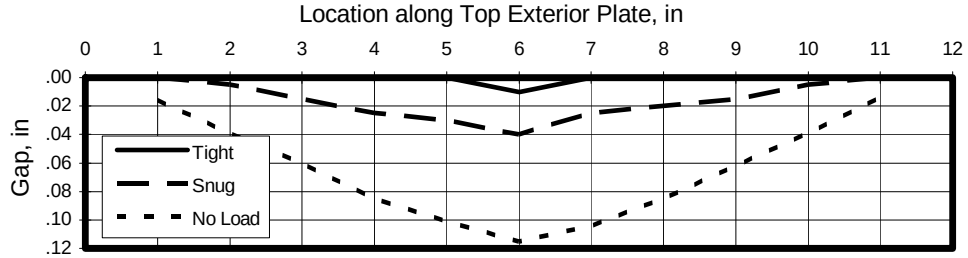


Figure A.30: Back Gap Between Interior Plate and Top Exterior Plate CD3TN124.OTM

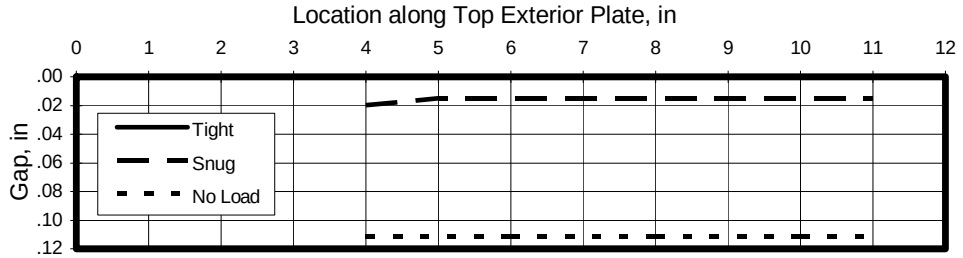


Figure A.31: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN124.OTM

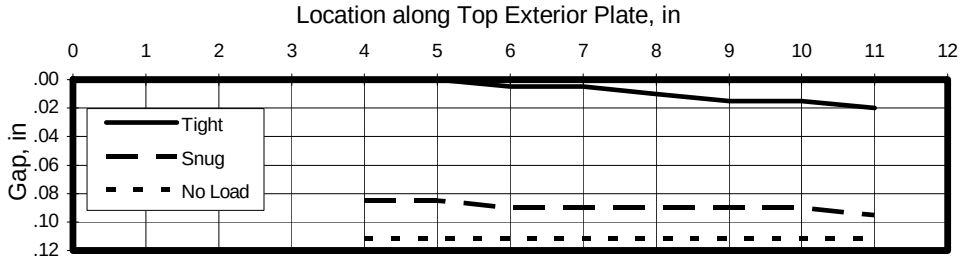


Figure A.32: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3TN124.OTM

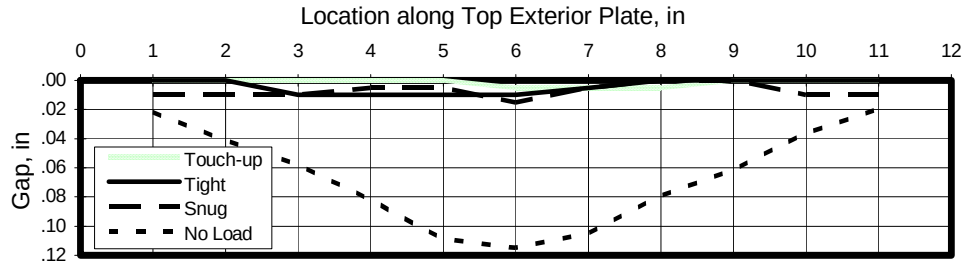


Figure A.33: Front Gap Between Interior Plate and Top Exterior Plate CD3CW252.MTO

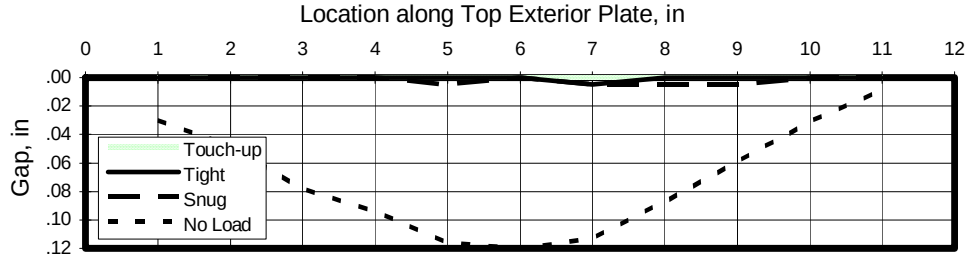


Figure A.34: Back Gap Between Interior Plate and Top Exterior Plate CD3CW252.MTO

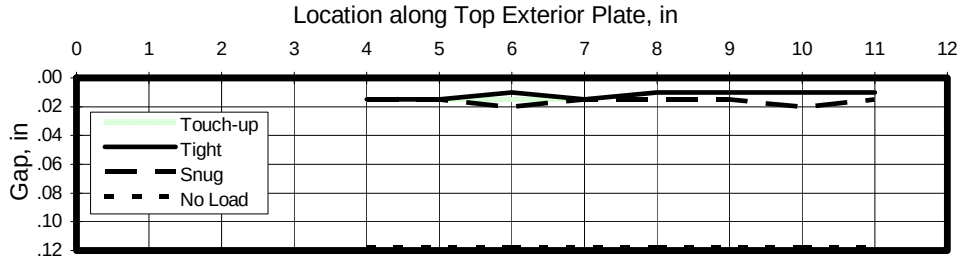


Figure A.35: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW252.MTO

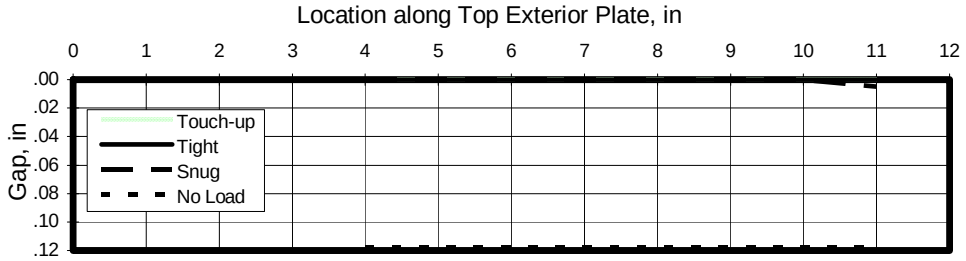


Figure A.36: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW252.MTO

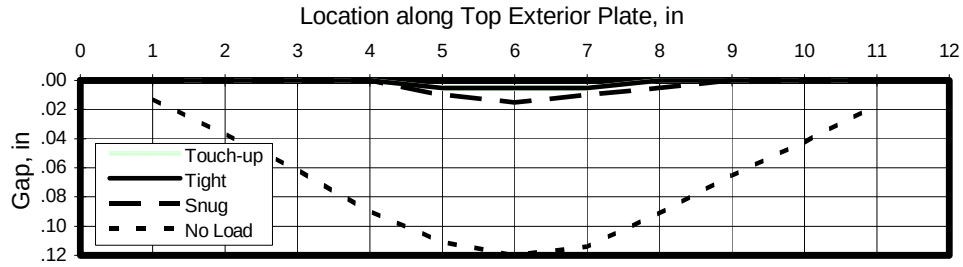


Figure A.37: Front Gap Between Interior Plate and Top Exterior Plate CD3CW253.MTO

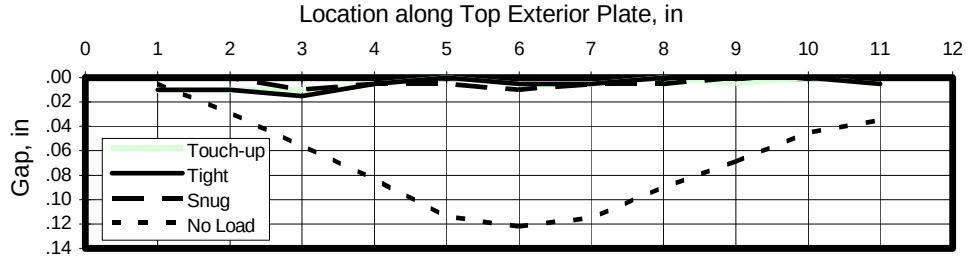


Figure A.38: Back Gap Between Interior Plate and Top Exterior Plate CD3CW253.MTO

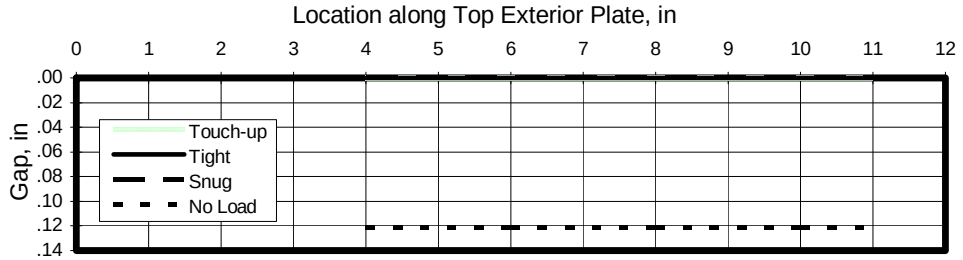


Figure A.39: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW253.MTO

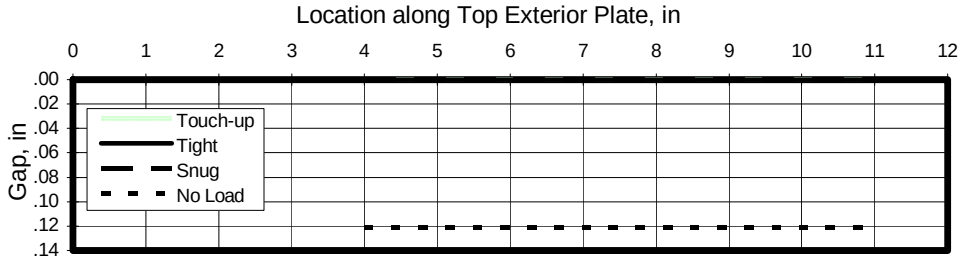


Figure A.40: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW253.MTO

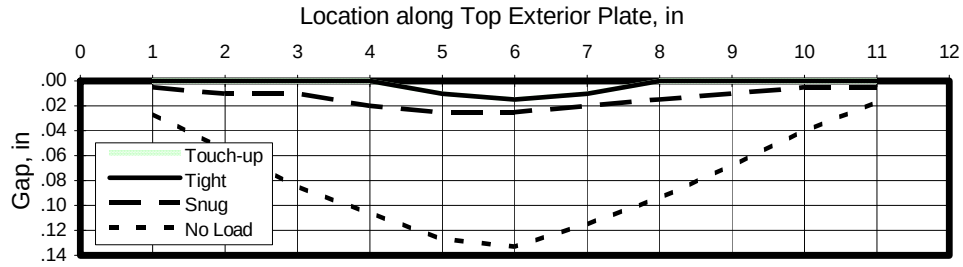


Figure A.41: Front Gap Between Interior Plate and Top Exterior Plate CD3CW254.MTO

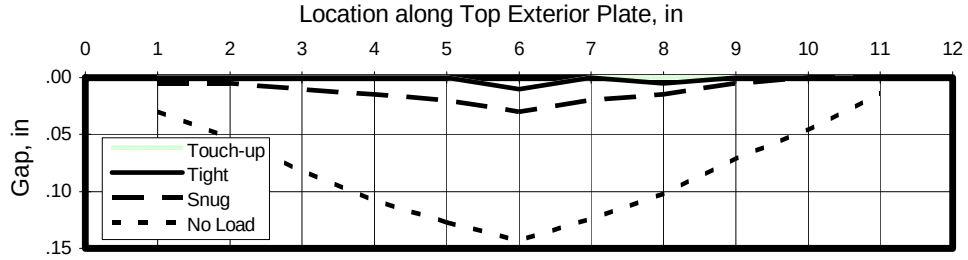


Figure A.42: Back Gap Between Interior Plate and Top Exterior Plate CD3CW254.MTO

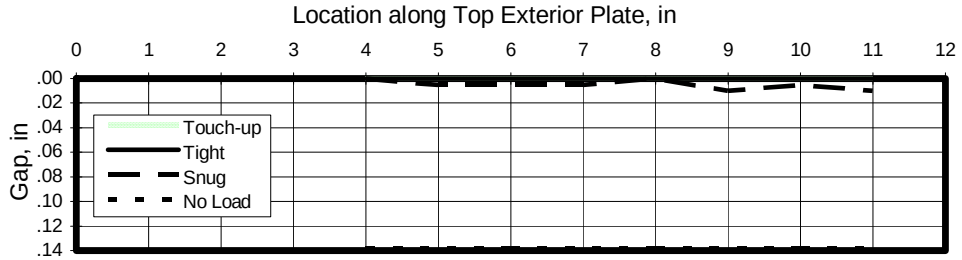


Figure A.43: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW254.MTO

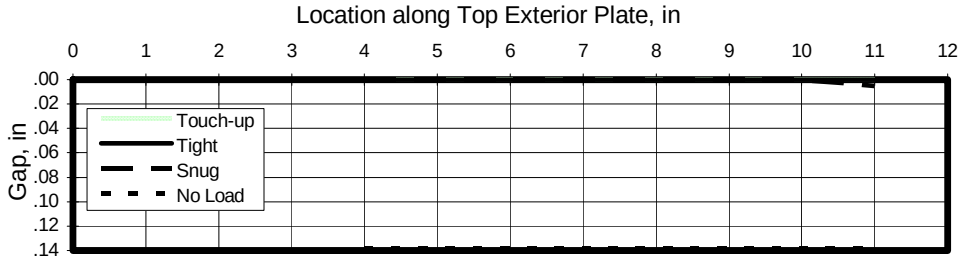


Figure A.44: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW254.MTO

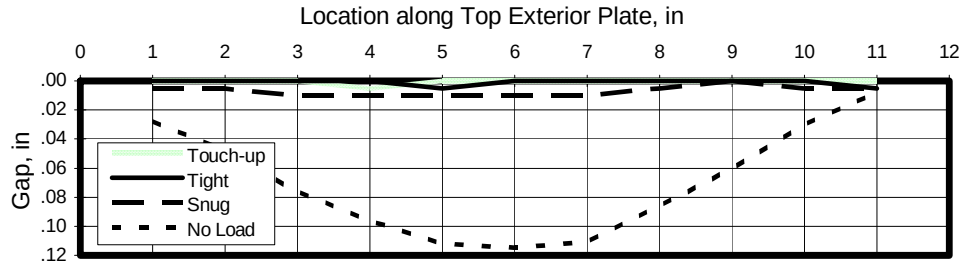


Figure A.45: Front Gap Between Interior Plate and Top Exterior Plate CD3CW122.LTR

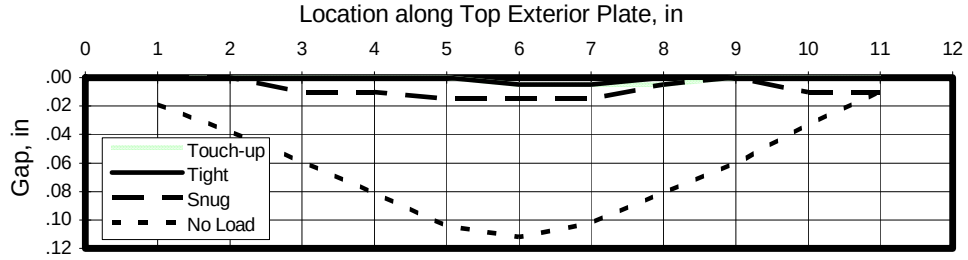


Figure A.46: Back Gap Between Interior Plate and Top Exterior Plate CD3CW122.LTR

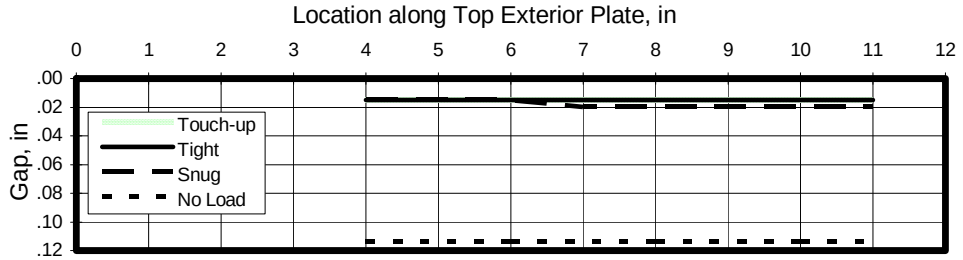


Figure A.47: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW122.LTR

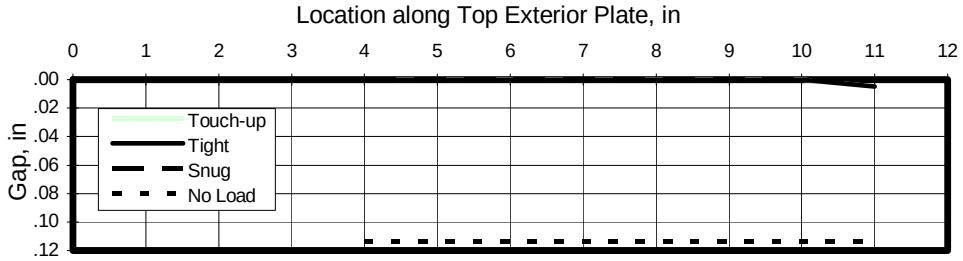


Figure A.48: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW122.LTR

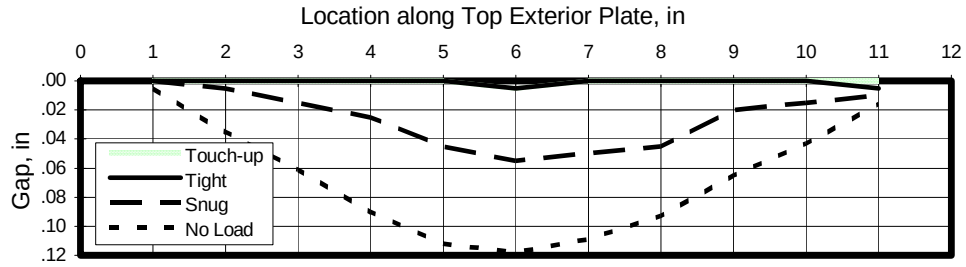


Figure A.49: Front Gap Between Interior Plate and Top Exterior Plate CD3CW123.LTR

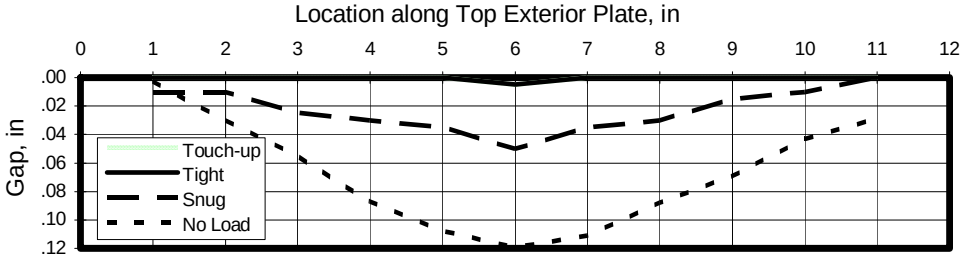


Figure A.50: Back Gap Between Interior Plate and Top Exterior Plate CD3CW123.LTR

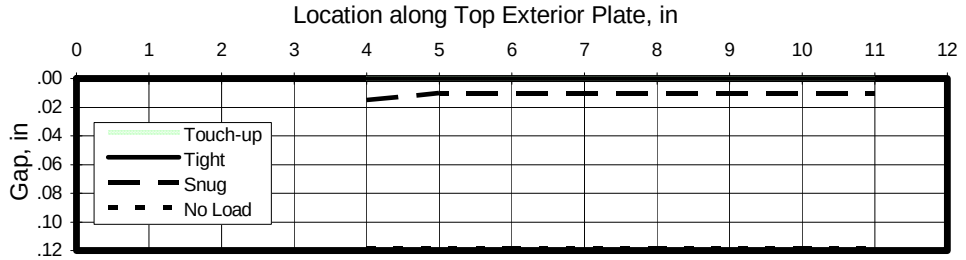


Figure A.51: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW123.LTR

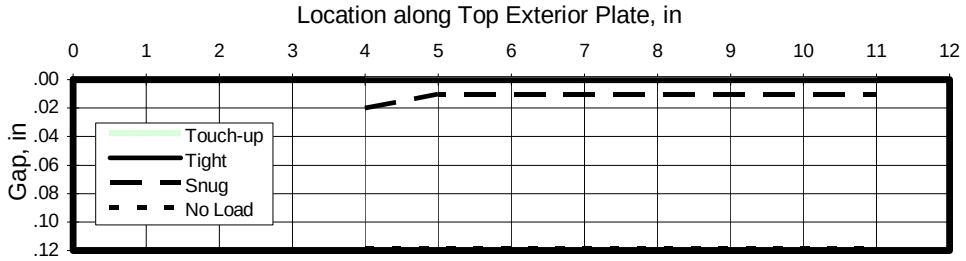


Figure A.52: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW123.LTR

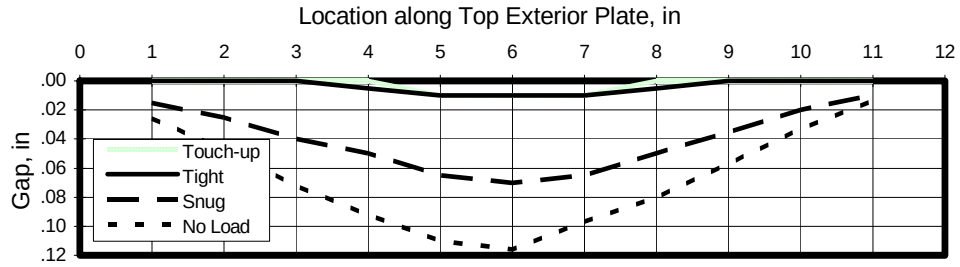


Figure A.53: Front Gap Between Interior Plate and Top Exterior Plate CD3CW124.LTR

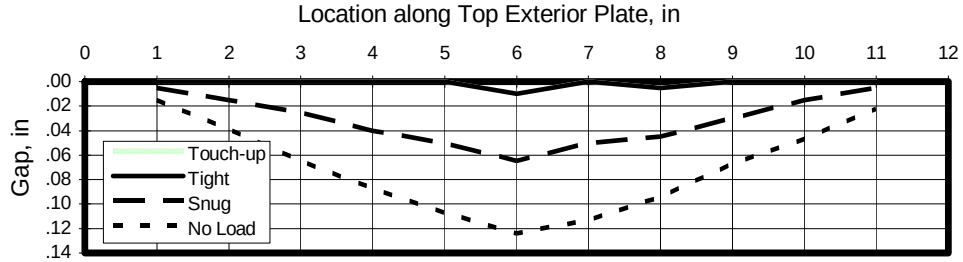


Figure A.54: Back Gap Between Interior Plate and Top Exterior Plate CD3CW124.LTR

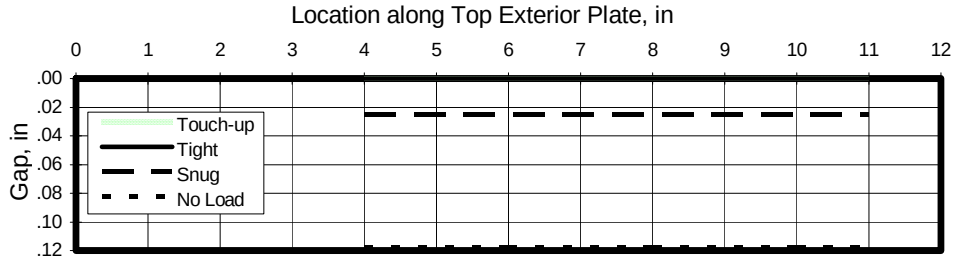


Figure A.55: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW124.LTR

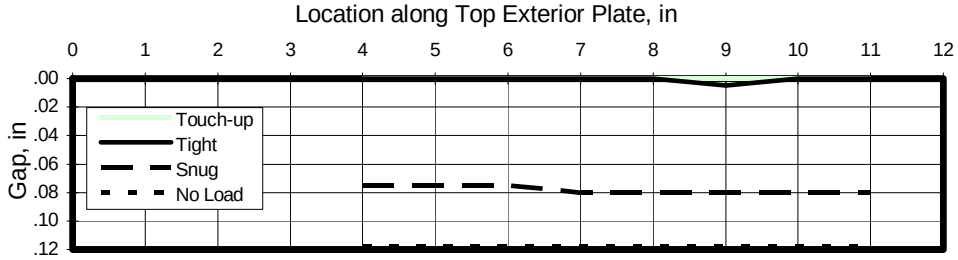


Figure A.56: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW124.LTR

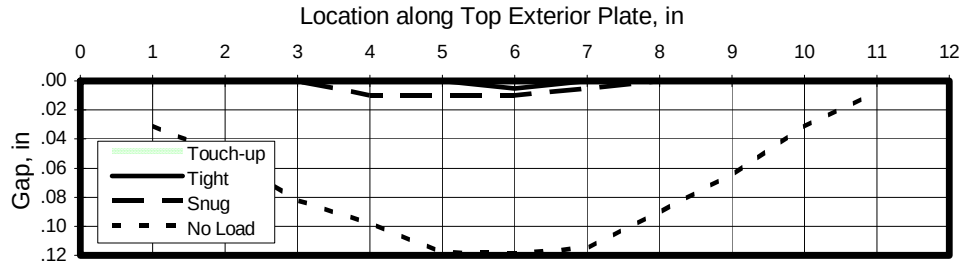


Figure A.57: Front Gap Between Interior Plate and Top Exterior Plate CD3CW122.OTM

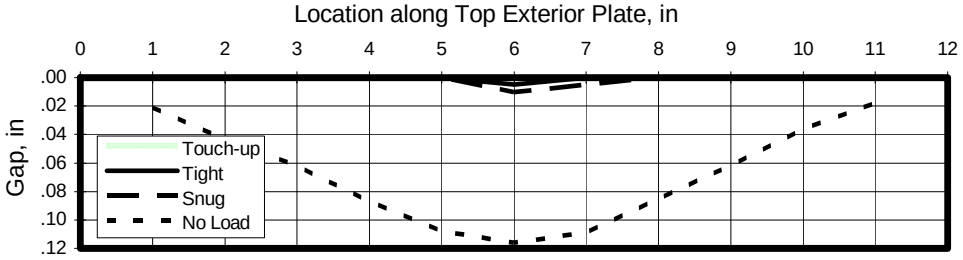


Figure A.58: Back Gap Between Interior Plate and Top Exterior Plate CD3CW122.OTM

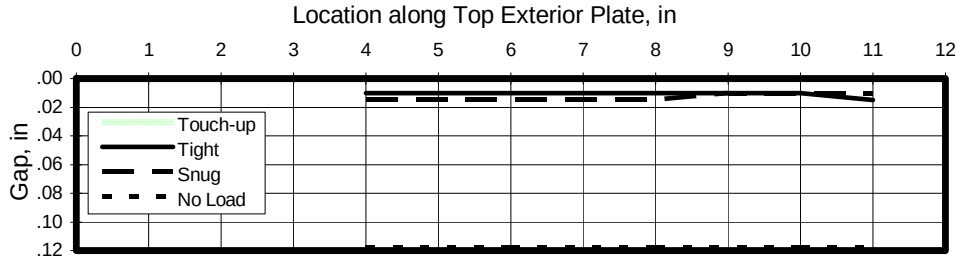


Figure A.59: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW122.OTM

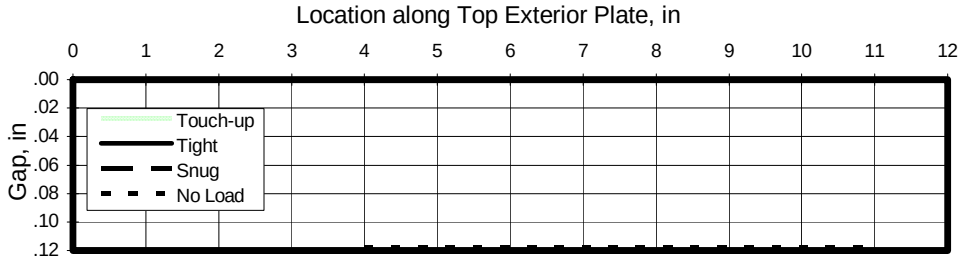


Figure A.60: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW122.OTM

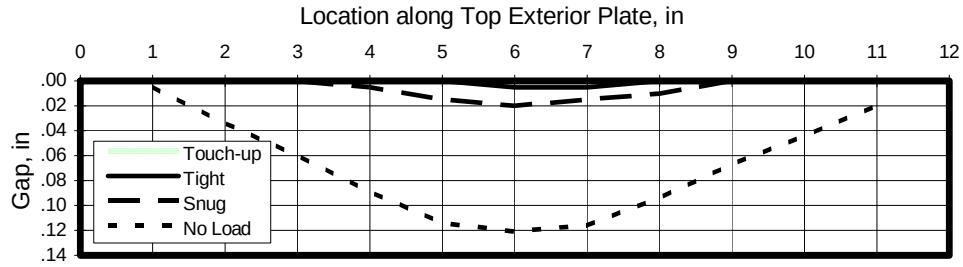


Figure A.61: Front Gap Between Interior Plate and Top Exterior Plate CD3CW123.OTM

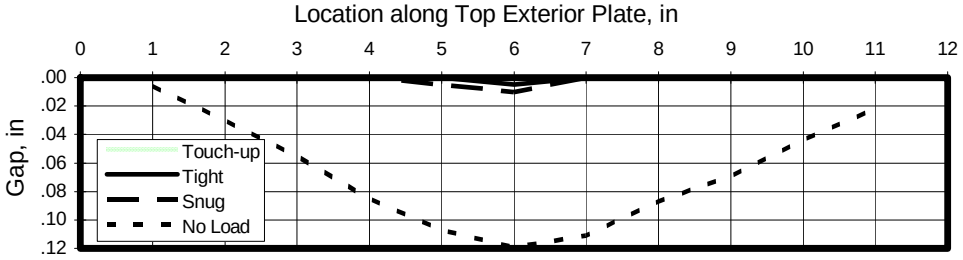


Figure A.62: Back Gap Between Interior Plate and Top Exterior Plate CD3CW123.OTM

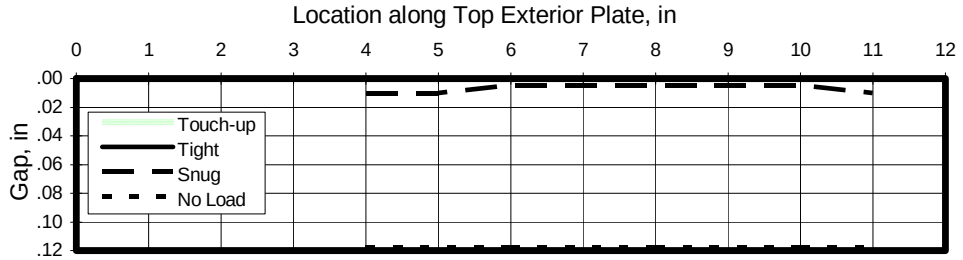


Figure A.63: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW123.OTM

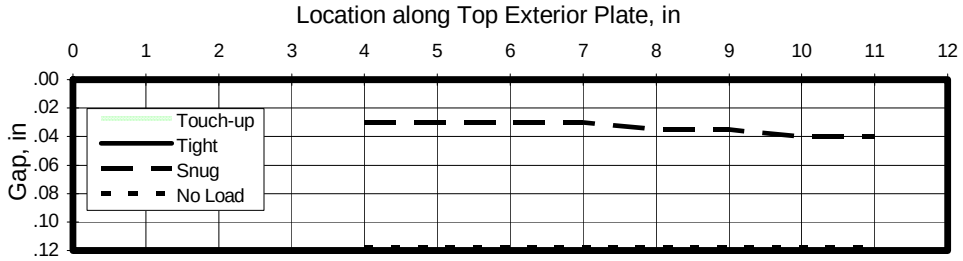


Figure A.64: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW123.OTM

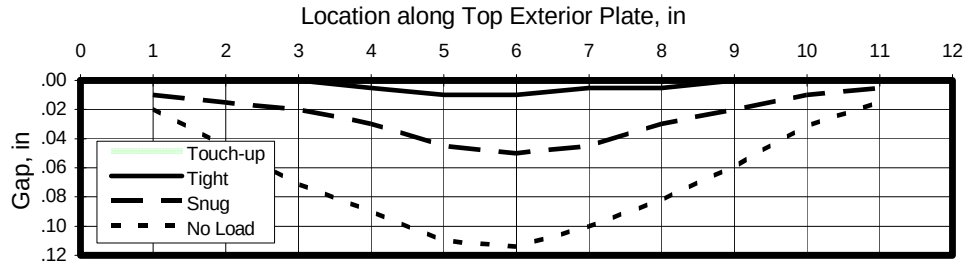


Figure A.65: Front Gap Between Interior Plate and Top Exterior Plate CD3CW124.OTM

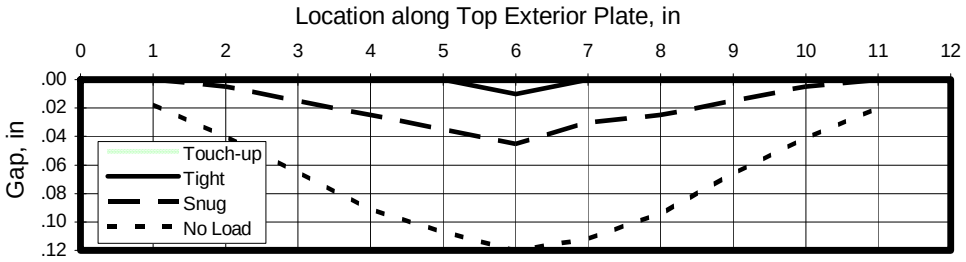


Figure A.66: Back Gap Between Interior Plate and Top Exterior Plate CD3CW124.OTM

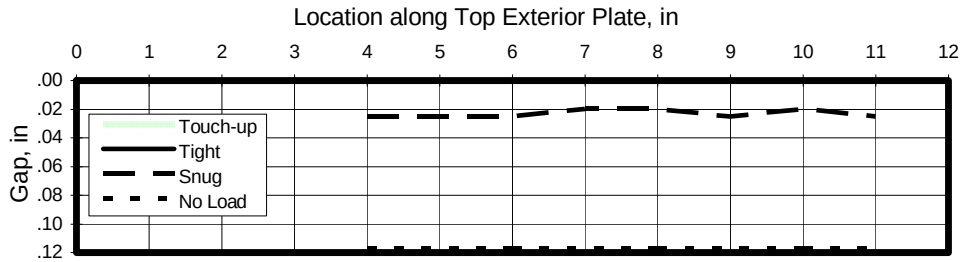


Figure A.67: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW124.OTM

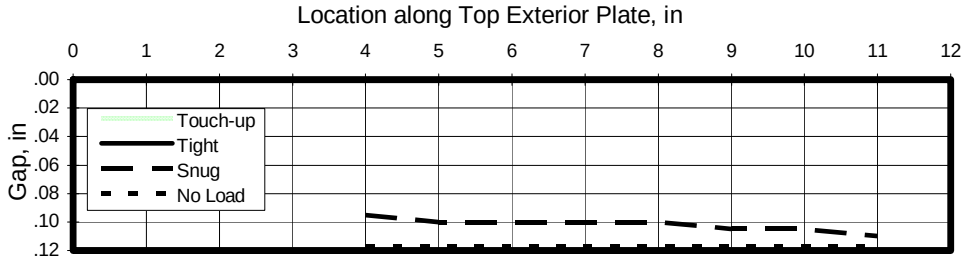


Figure A.68: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD3CW124.OTM

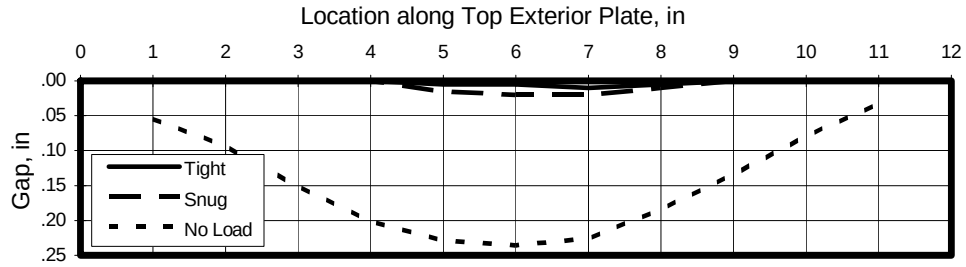


Figure A.69: Front Gap Between Interior Plate and Top Exterior Plate CD6TN122.MTO

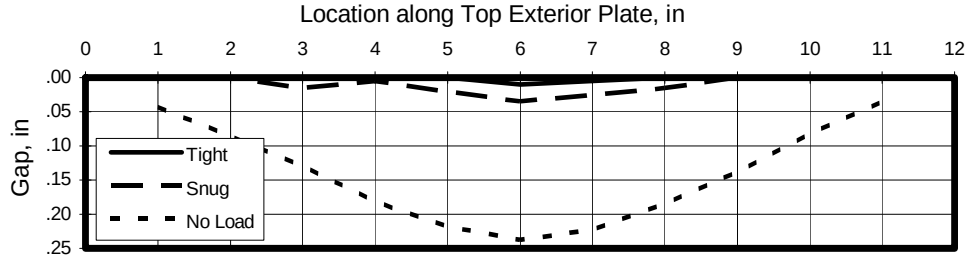


Figure A.70: Back Gap Between Interior Plate and Top Exterior Plate CD6TN122.MTO

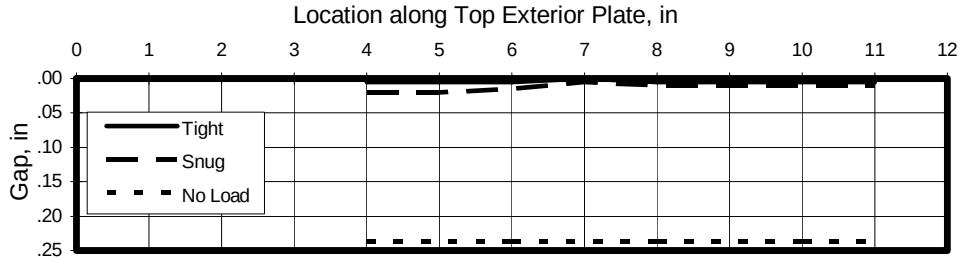


Figure A.71: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6TN122.MTO

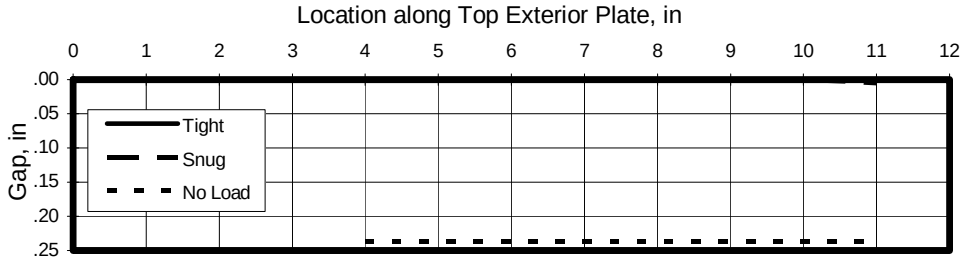


Figure A.72: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6TN122.MTO

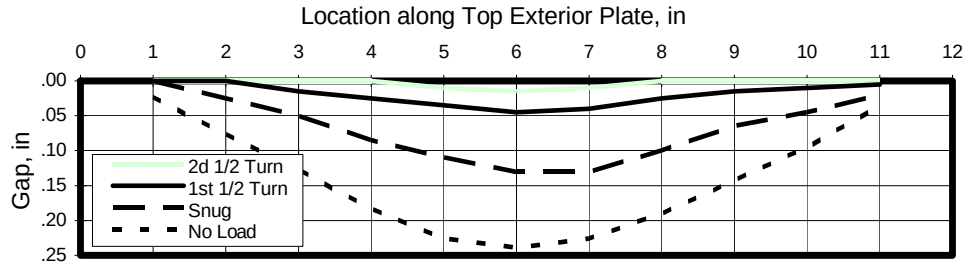


Figure A.73: Front Gap Between Interior Plate and Top Exterior Plate CD6TN123.MTO

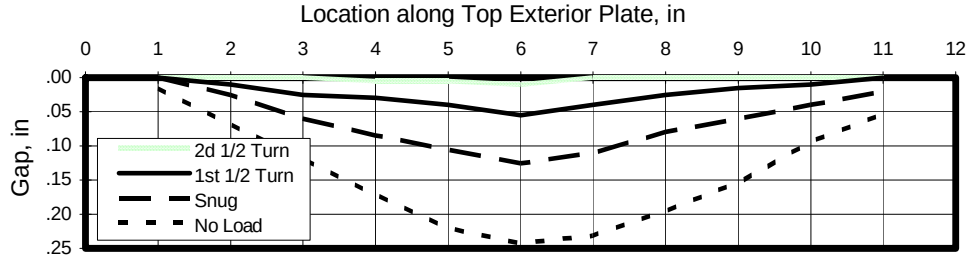


Figure A.74: Back Gap Between Interior Plate and Top Exterior Plate CD6TN123.MTO

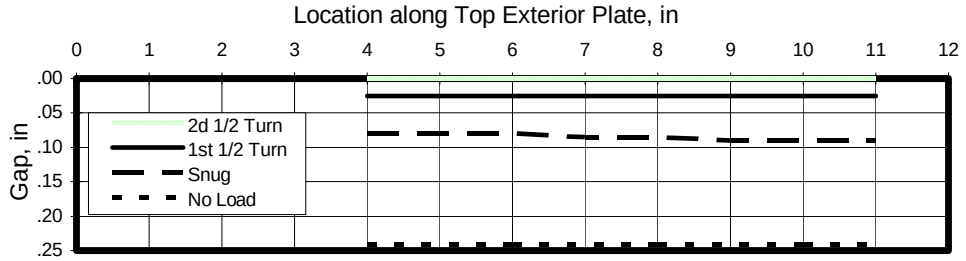


Figure A.75: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6TN123.MTO

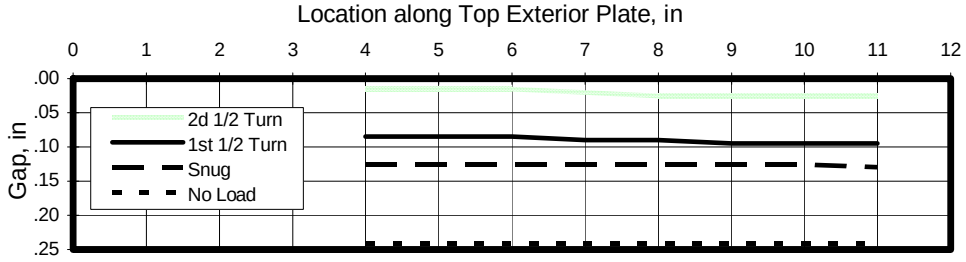


Figure A.76: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6TN123.MTO

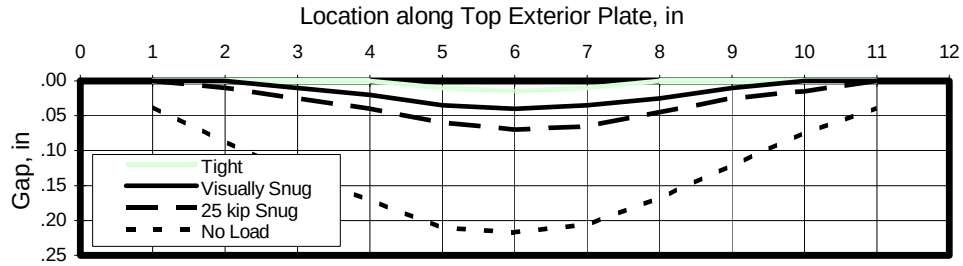


Figure A.77: Front Gap Between Interior Plate and Top Exterior Plate CD6TN254.MTO

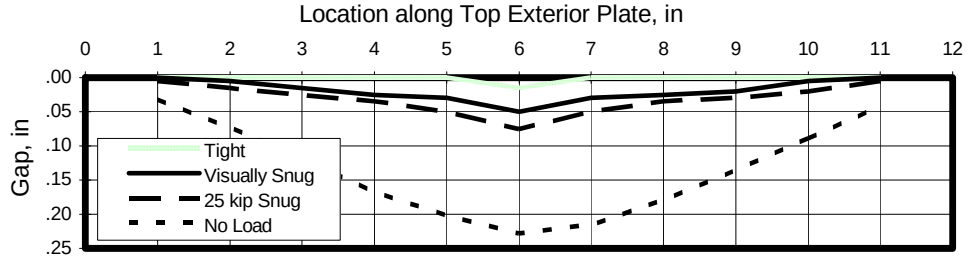


Figure A.78: Back Gap Between Interior Plate and Top Exterior Plate CD6TN254.MTO

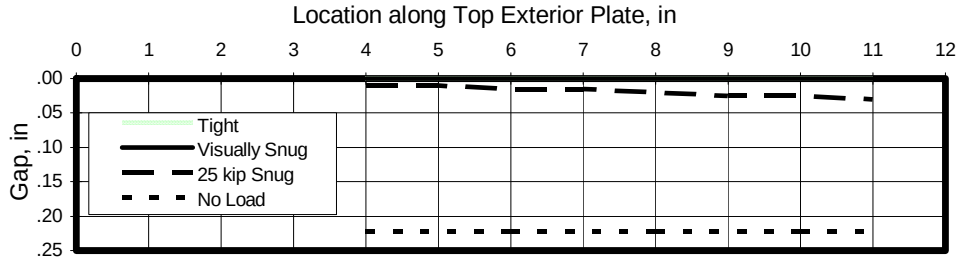


Figure A.79: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6TN254.MTO

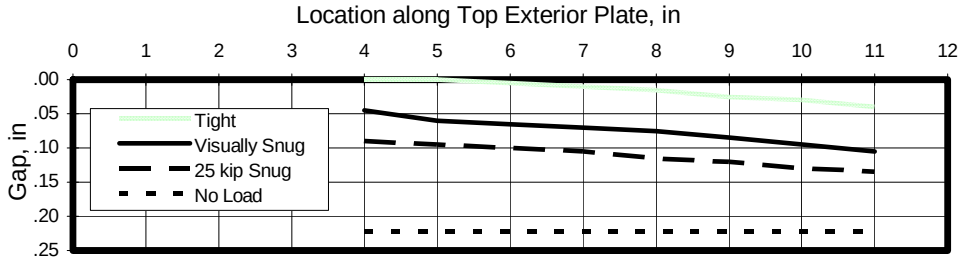


Figure A.80: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6TN254.MTO

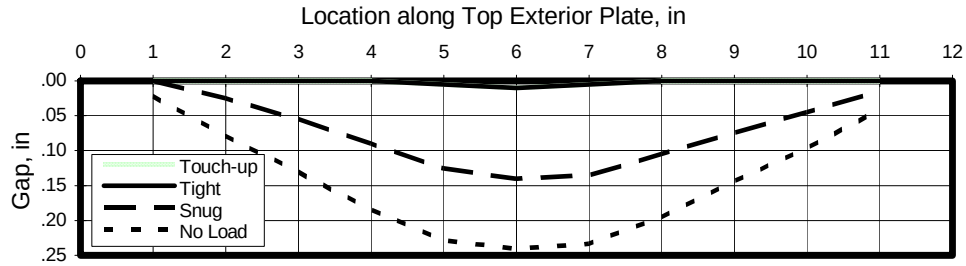


Figure A.81: Front Gap Between Interior Plate and Top Exterior Plate CD6CW123.MTO

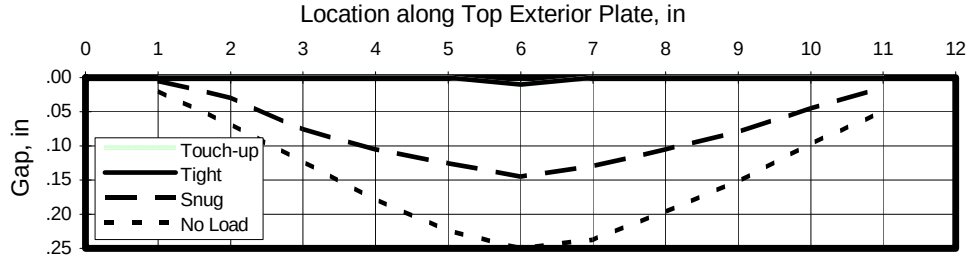


Figure A.82: Back Gap Between Interior Plate and Top Exterior Plate CD6CW123.MTO

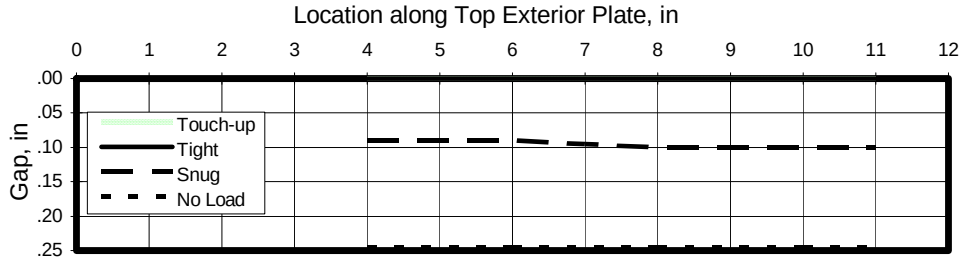


Figure A.83: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6CW123.MTO

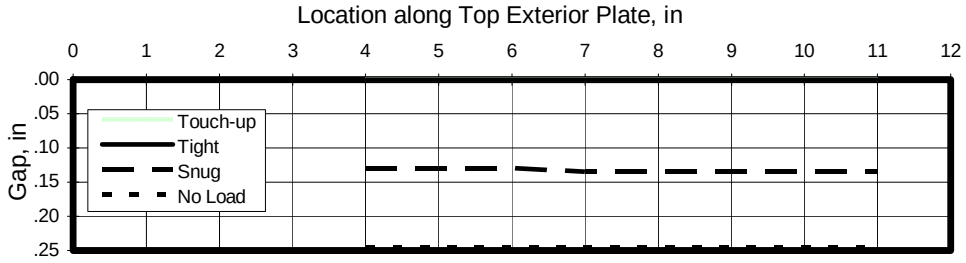


Figure A.84: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6CW123.MTO

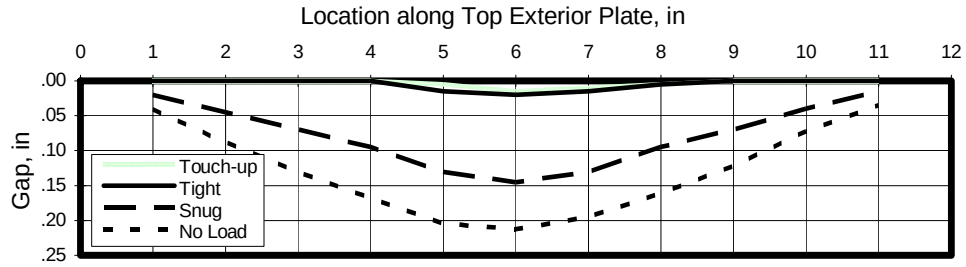


Figure A.85: Front Gap Between Interior Plate and Top Exterior Plate CD6CW124.MTO

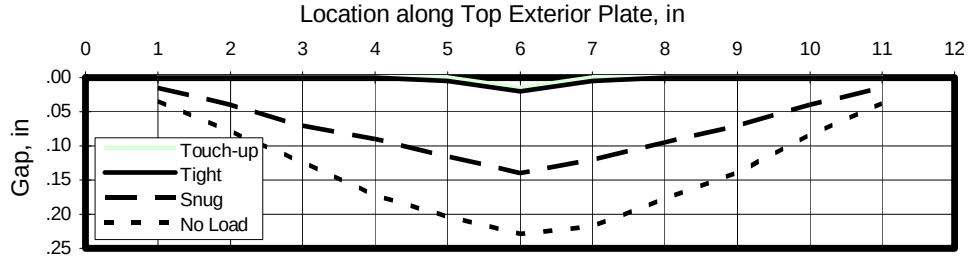
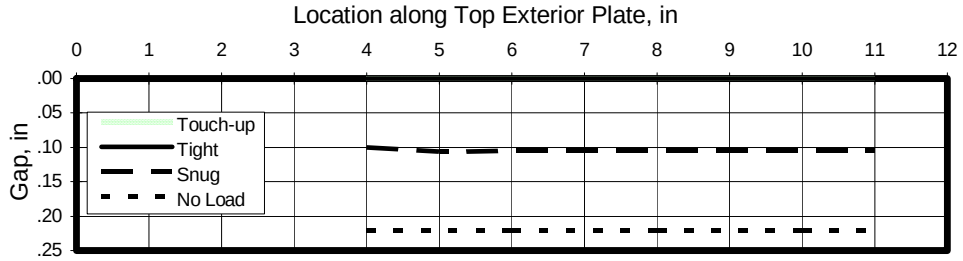


Figure A.86: Back Gap Between Interior Plate and Top Exterior Plate CD6CW124.MTO



FigureA.87: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6CW124.MTO

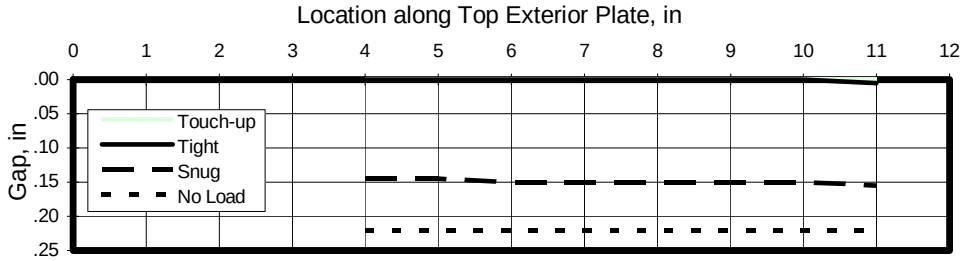


Figure A.88: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6CW124.MTO

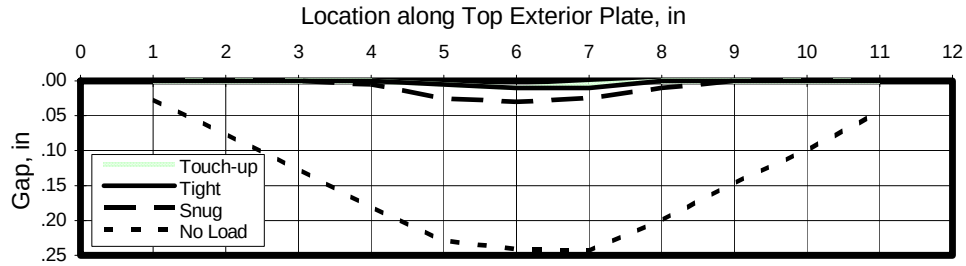


Figure A.89: Front Gap Between Interior Plate and Top Exterior Plate CD6CW253.MTO

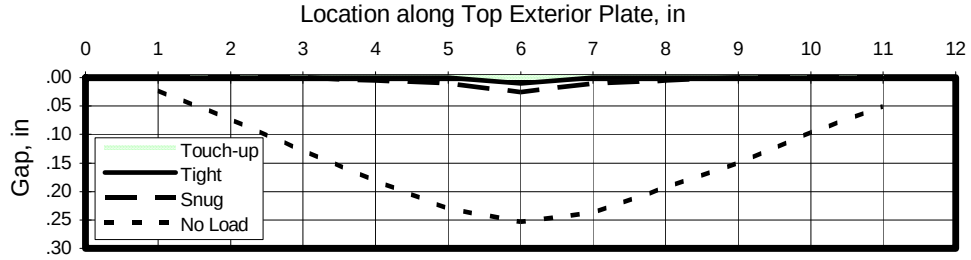


Figure A.90: Back Gap Between Interior Plate and Top Exterior Plate CD6CW253.MTO

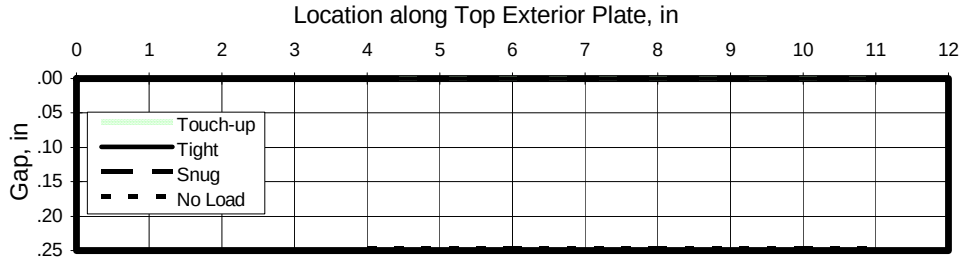


Figure A.91: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6CW253.MTO

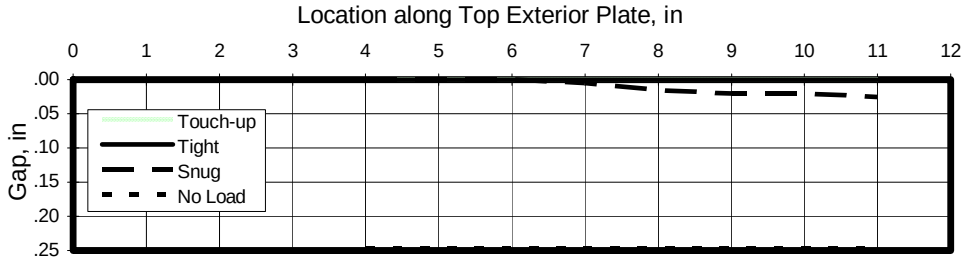


Figure A.92: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6CW253.MTO

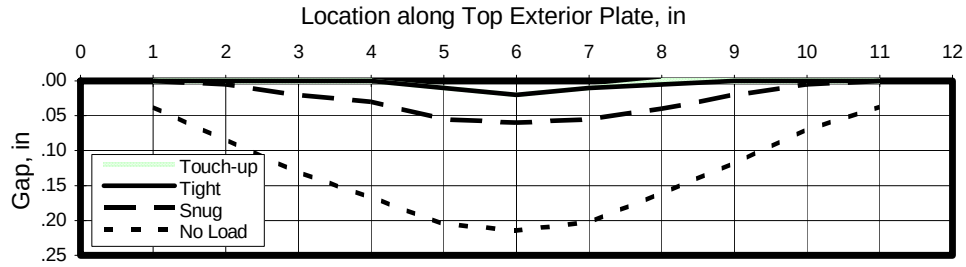


Figure A.93: Front Gap Between Interior Plate and Top Exterior Plate CD6CW254.MTO

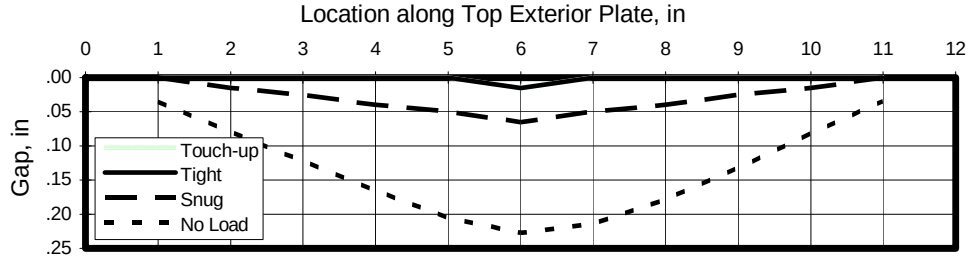


Figure A.94: Back Gap Between Interior Plate and Top Exterior Plate CD6CW254.MTO

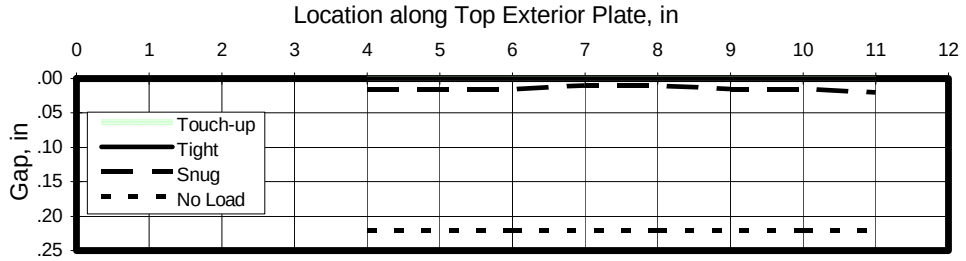


Figure A.95: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6CW254.MTO

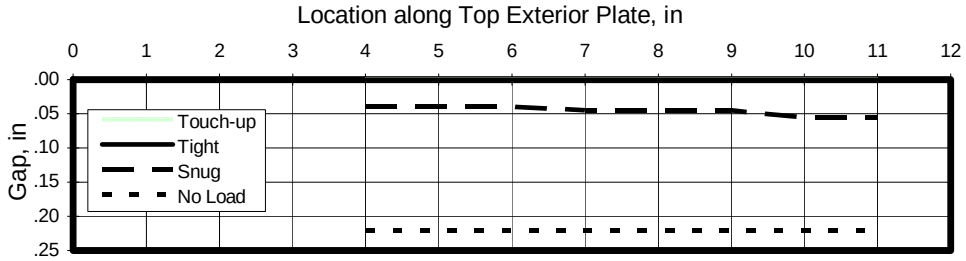


Figure A.96: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. CD6CW254.MTO

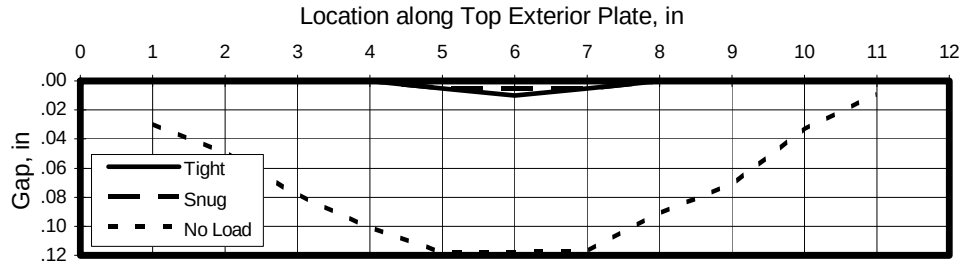


Figure A.97: Front Gap Between Interior Plate and Top Exterior Plate HD3CS412.MTO

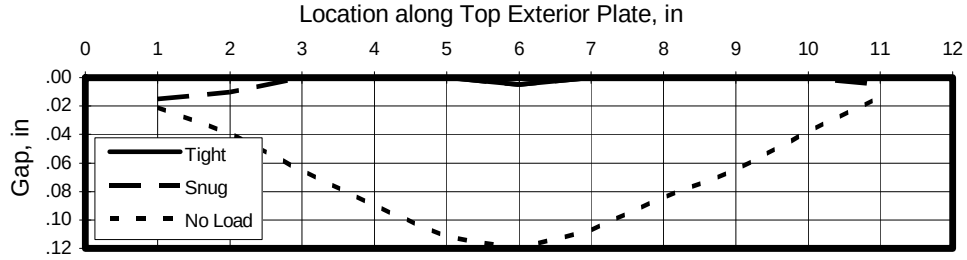


Figure A.98: Back Gap Between Interior Plate and Top Exterior Plate HD3CS412.MTO

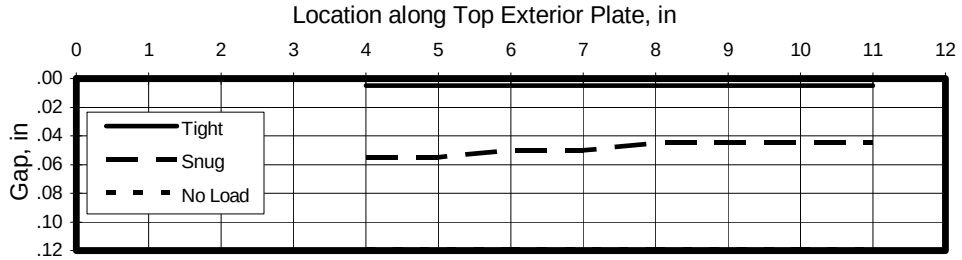


Figure A.99: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. HD3CS412.MTO

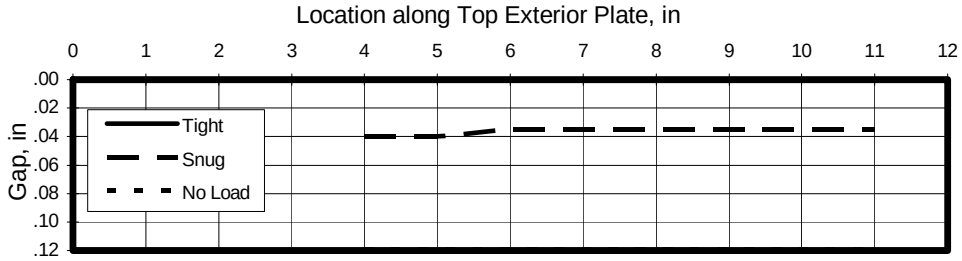


Figure A.100: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. HD3CS412.MTO

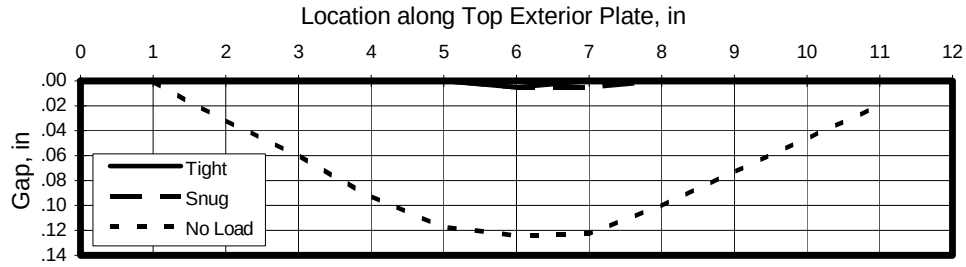


Figure A.101: Front Gap Between Interior Plate and Top Exterior Plate HD3CS413.MTO

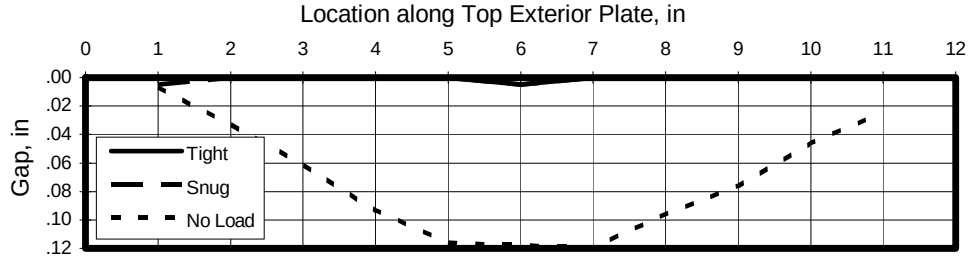


Figure A.102: Back Gap Between Interior Plate and Top Exterior Plate HD3CS413.MTO

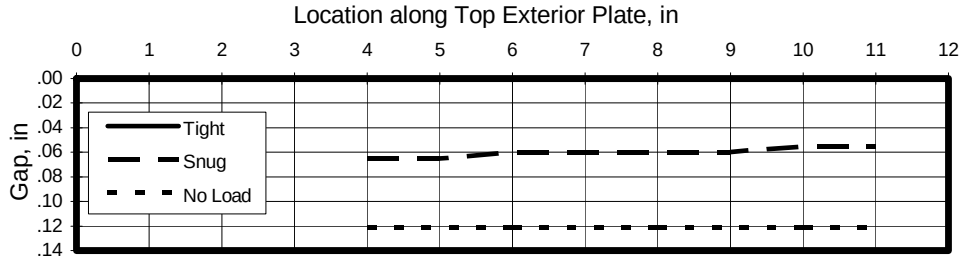


Figure A.103: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. HD3CS413.MTO

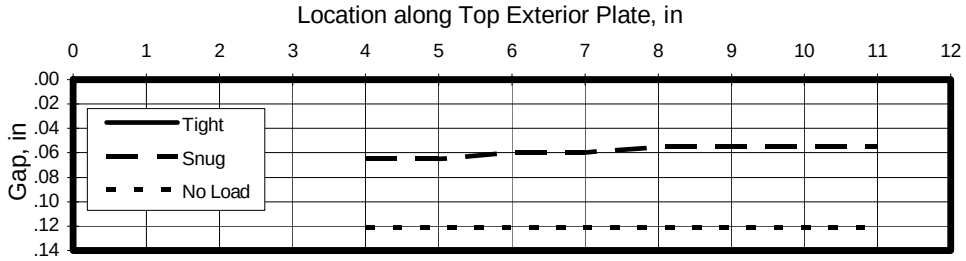


Figure A.104: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. HD3CS413.MTO

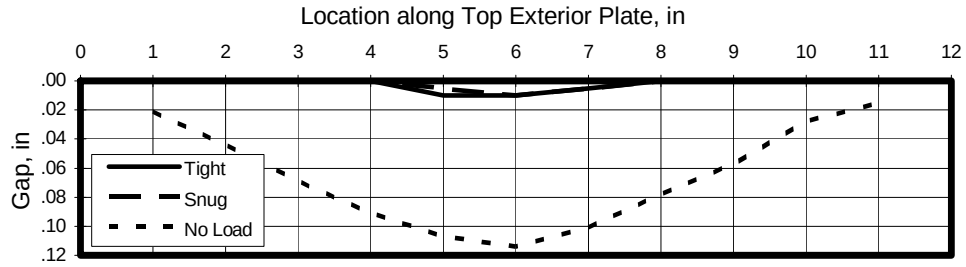


Figure A.105: Front Gap Between Interior Plate and Top Exterior Plate HD3CS414.MTO

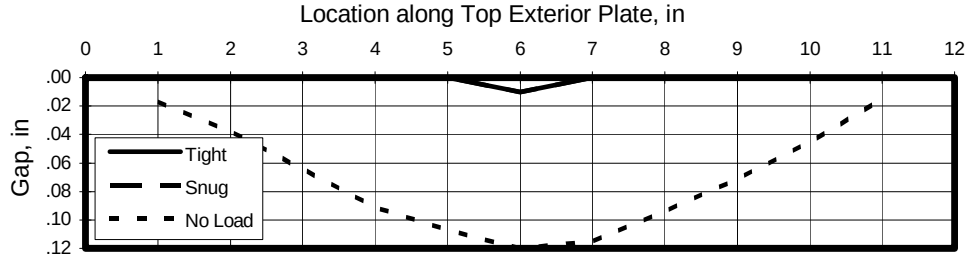


Figure A.106: Back Gap Between Interior Plate and Top Exterior Plate HD3CS414.MTO

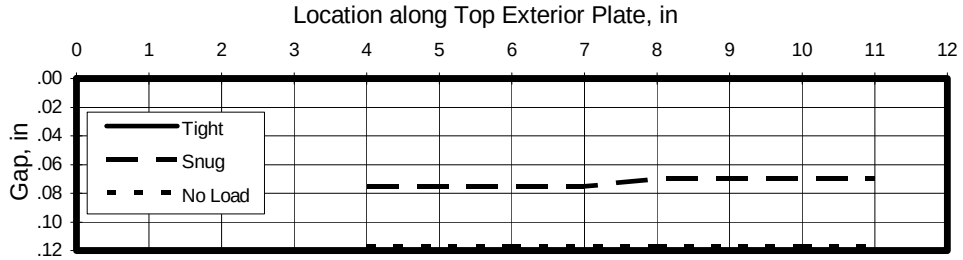


Figure A.107: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. HD3CS414.MTO

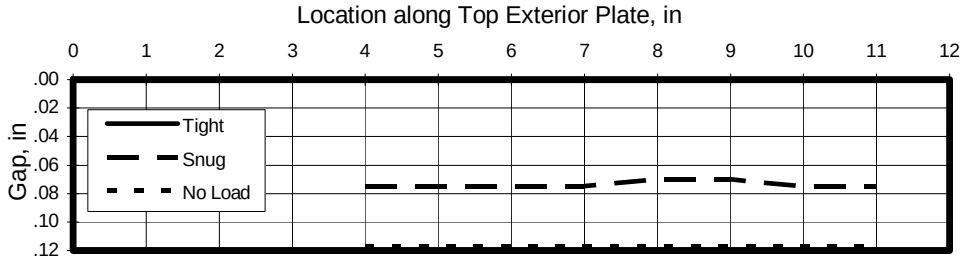


Figure A.108: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. HD3CS414.MTO

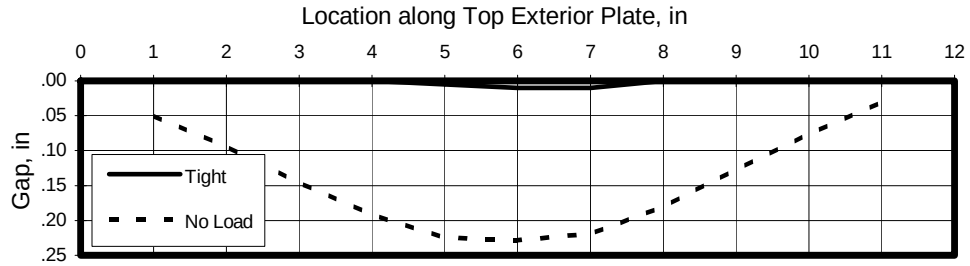
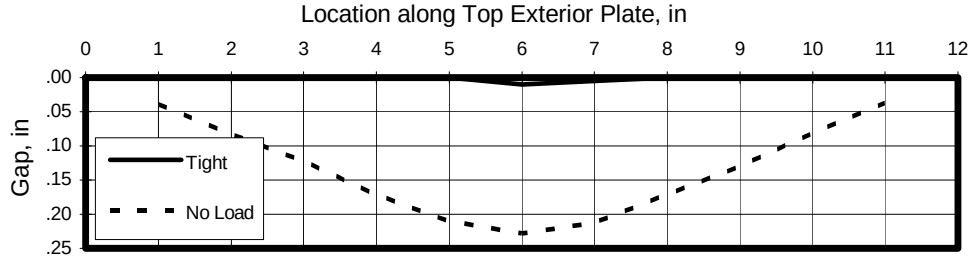


Figure A.109: Front Gap Between Interior Plate and Top Exterior Plate HD6NS--2.MTO



FigureA.110: Back Gap Between Interior Plate and Top Exterior Plate HD6NS--2.MTO

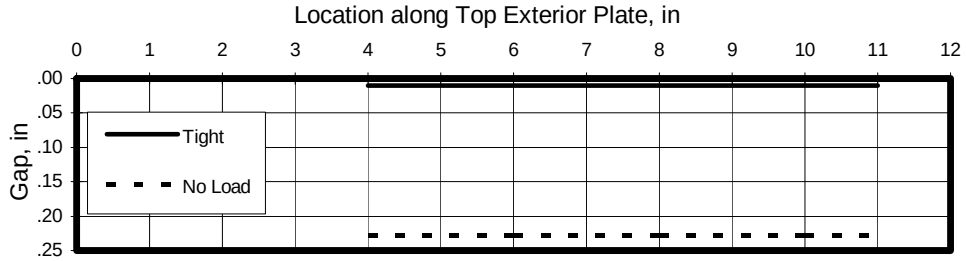


Figure A.111: Left Side Gap Between Interior Plt. and Bottom Exterior Plt. HD6NS--2.MTO

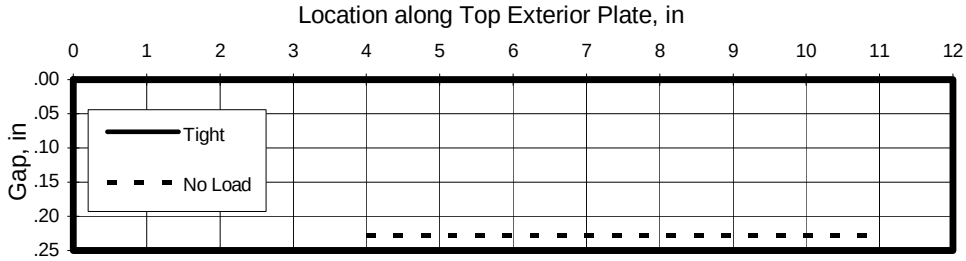


Figure A.112: Right Side Gap Between Interior Plt. and Bottom Exterior Plt. HD6NS--2.MTO

APPENDIX B

RESULTS OF CONNECTION TESTS WITH CONVENTIONAL FASTENERS

INDEX OF FIGURES

		Fastener Number											
		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	10.4	-0.6	-0.6	-0.6	-0.7	-0.8	-0.7	-0.6	-0.6	-0.6	-0.5	-0.6
	5	4.3	10.0	-0.8	-0.7	-0.7	-0.9	-0.9	-0.8	-0.8	-0.8	-0.8	-0.8
	6	5.0	4.5	10.2	-0.7	-0.7	-0.7	-0.9	-0.7	-0.7	-0.8	-0.7	-0.7
	7	2.7	3.4	9.6	8.5	-0.8	-0.8	-0.9	-0.8	-0.7	-0.8	-0.8	-0.8
	8	2.8	2.3	8.6	4.2	8.5	-1.0	-1.0	-0.9	-0.8	-0.9	-0.9	-0.8
	9	3.6	3.2	6.9	4.8	5.4	7.1	-0.3	-0.2	-0.2	-0.2	-0.3	-0.2
	1	2.9	2.6	6.3	5.3	5.9	6.8	9.4	-0.1	0.0	-0.1	-0.2	-0.1
	2	3.2	2.4	5.4	5.4	6.1	6.9	9.2	9.9	-0.1	-0.1	-0.2	-0.1
	3	3.1	2.6	5.7	5.3	6.2	6.8	9.1	9.2	9.3	-0.1	-0.2	-0.1
	10	3.9	2.9	6.1	3.7	4.9	6.2	9.0	9.1	8.7	11.1	-0.2	-0.1
	11	3.9	3.1	6.5	4.0	4.8	5.4	9.0	9.2	8.6	10.9	10.7	-0.1
	12	3.9	3.1	6.8	4.0	5.0	4.7	8.9	9.1	8.6	10.8	10.0	10.5
Tightening Order	4	53.7	2.9	7.0	3.7	5.1	5.1	9.7	9.4	8.5	10.8	9.8	10.0
	5	53.0	52.5	6.4	3.8	3.9	5.0	9.7	10.0	8.5	10.8	9.8	10.1
	6	52.9	52.0	53.8	3.8	4.0	3.6	9.7	10.0	9.2	10.8	9.8	10.1
	7	52.8	51.7	53.3	47.5	3.5	3.7	9.6	10.0	9.0	11.2	10.0	10.0
	8	52.8	51.8	53.4	47.0	50.1	3.3	9.7	10.0	9.2	11.3	10.5	10.1
	9	52.8	51.8	53.2	46.9	48.9	49.9	9.7	10.1	8.9	11.3	10.5	10.9
	1	52.8	51.8	53.1	46.8	48.7	49.3	55.6	10.3	8.9	11.2	10.5	10.9
	2	52.8	51.8	53.1	46.7	48.6	49.1	55.0	55.2	9.0	11.2	10.5	10.9
	3	52.8	51.8	53.2	46.7	48.5	48.9	54.9	54.5	51.4	11.2	10.5	10.9
	10	52.8	51.8	53.2	46.6	48.4	48.8	54.8	54.3	51.0	53.0	10.8	10.9
	11	52.7	51.7	53.1	46.5	48.3	48.6	54.7	54.2	51.0	52.4	56.4	11.1
	12	52.7	51.7	53.1	46.5	48.2	48.6	54.6	54.1	50.9	52.2	56.1	53.9

Tension in Kips

Average Fastener Tension
(after snugging) = 7.1 Kips
(after tightening) = 51.9 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Middle to Outside

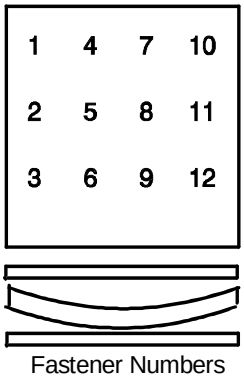


Figure B.1: Fastener Tensions for test CD3TN122.MTO

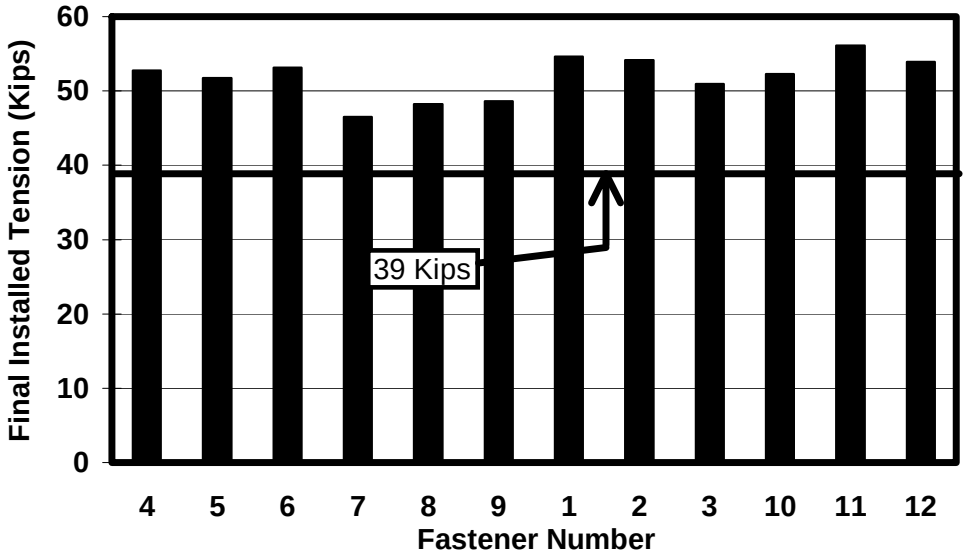


Figure B.2: **Final Installed Tensions for Test CD3TN122.MTO**

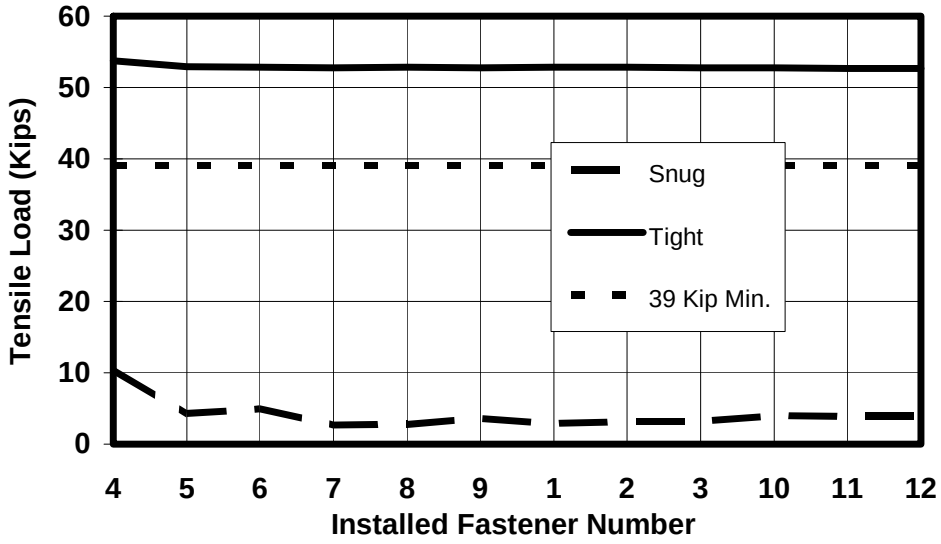


Figure B.3: **Tensile Load History for Fastener #4 - Test CD3TN122.MTO**

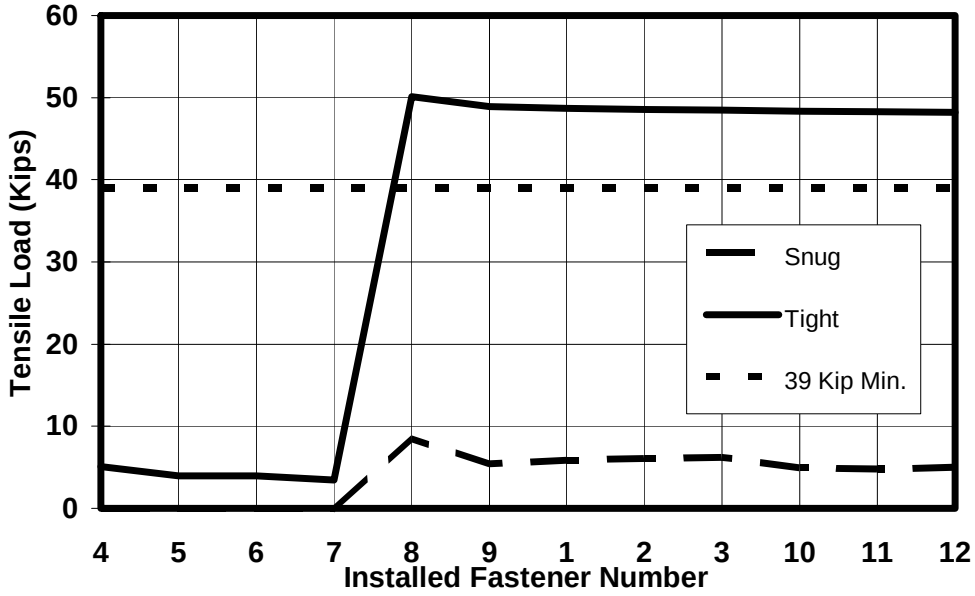


Figure B.4: **Tensile Load History for Fastener #8 - Test CD3TN122.MTO**

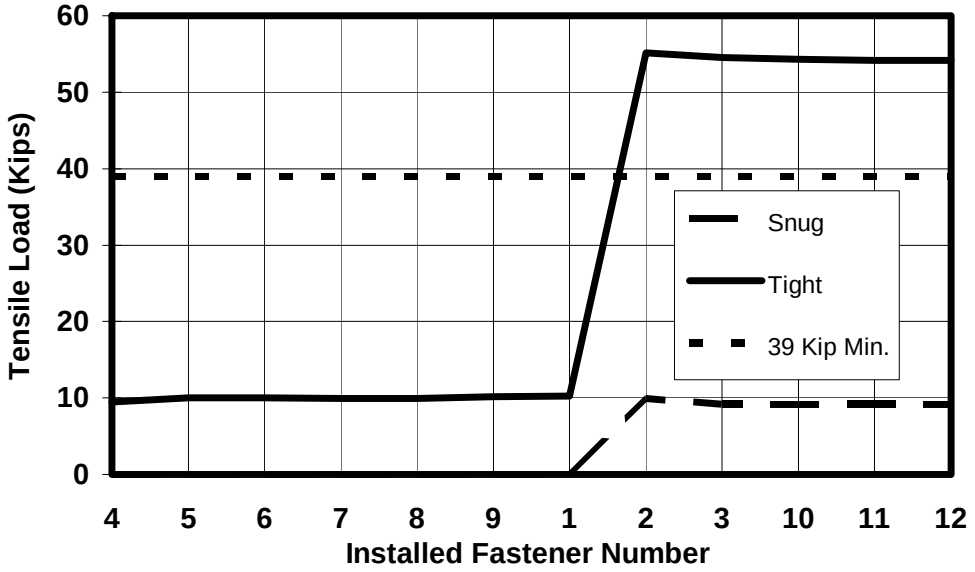


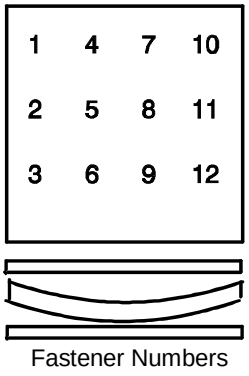
Figure B.5: **Tensile Load History for Fastener #2 - Test CD3TN122.MTO**

		Fastener Number											
		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	12.1	-0.1	0.0	0.0	0.1	0.1	0.0	-0.1	-0.1	0.3	0.5	0.0
	5	4.1	12.9	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.6	0.3	0.0
	6	4.5	4.3	11.4	-0.1	-0.1	0.1	0.0	-0.1	-0.2	0.6	0.2	-0.1
	7	0.8	2.9	12.0	12.3	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0.2
	8	1.4	1.9	9.8	4.9	12.6	0.1	0.1	0.1	0.1	0.1	0.1	0.0
	9	2.1	2.6	6.6	4.8	3.6	13.5	0.0	0.0	0.0	0.1	0.1	0.0
	1	0.0	0.0	1.7	7.7	5.7	16.3	13.3	0.0	0.0	0.1	0.0	0.0
	2	0.1	0.1	0.3	8.1	6.3	17.0	6.4	13.4	0.1	0.1	0.1	0.0
	3	0.1	0.1	0.0	8.2	6.7	17.5	7.3	5.9	13.6	0.1	0.1	0.1
	10	0.1	0.1	0.0	2.1	3.1	15.3	8.0	5.8	13.5	11.7	0.1	0.0
	11	0.1	0.0	0.0	2.5	2.3	12.2	7.9	5.8	14.1	3.7	12.8	0.0
	12	0.1	0.1	0.1	2.7	2.7	8.1	7.9	5.9	14.4	4.5	8.1	13.7
Tightening Order	4	53.7	0.4	0.5	0.2	0.8	8.1	7.4	6.3	14.1	4.8	8.5	13.7
	5	51.4	43.5	0.4	0.2	0.3	4.6	8.3	6.5	14.0	4.8	8.5	13.7
	6	51.4	41.4	53.1	0.1	0.2	1.2	8.4	7.2	12.2	4.8	8.6	12.8
	7	50.0	41.1	52.2	54.8	0.2	1.3	8.5	7.2	12.2	3.2	8.1	12.9
	8	50.1	40.0	51.5	53.7	55.7	1.1	8.5	7.2	12.2	3.6	7.5	12.8
	9	50.1	40.1	49.5	53.6	54.9	56.9	8.4	7.1	12.5	3.8	7.9	11.4
	1	50.2	40.3	49.5	53.4	54.7	56.3	59.3	7.0	12.8	3.8	7.9	11.5
	2	50.2	40.1	49.5	53.4	54.6	56.0	58.6	58.6	13.6	3.7	7.8	11.4
	3	50.3	40.4	49.6	53.2	54.5	56.0	58.5	58.2	58.7	3.8	7.9	11.6
	10	50.2	40.3	49.5	53.3	54.5	55.8	58.2	58.0	57.9	56.4	7.8	11.5
	11	50.1	40.2	49.4	53.2	54.5	55.7	58.2	57.9	57.7	55.6	59.4	12.0
	12	50.1	40.2	49.4	53.1	54.4	55.8	58.1	57.9	57.5	55.5	58.9	59.9

Tension in Kips

Average Fastener Tension
(after snugging) = 5.7 Kips
(after tightening) = 54.2 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Middle to Outside



Fastener Numbers

Figure B.6: Fastener Tensions for test CD3TN123.MTO

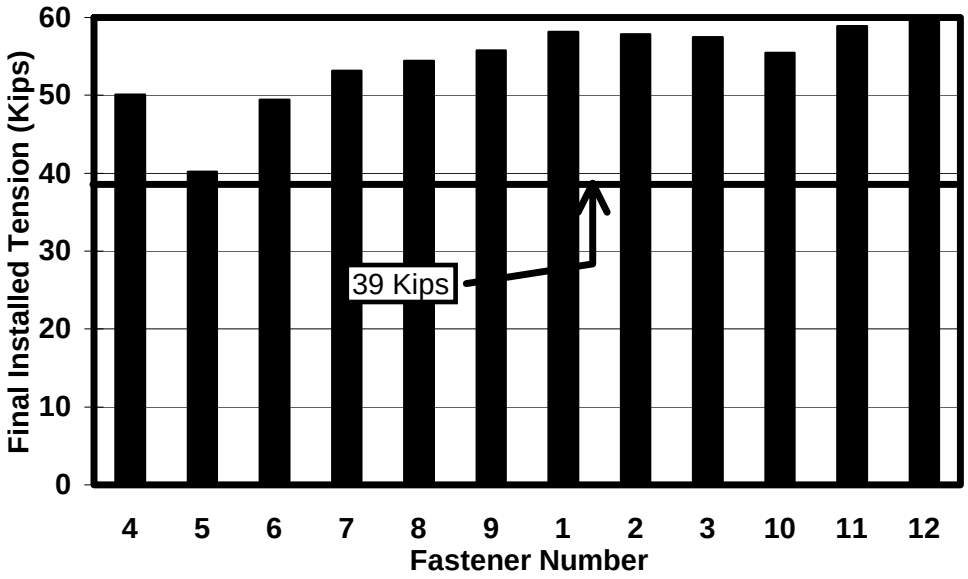


Figure B.7: **Final Installed Tensions for Test CD3TN123.MTO**

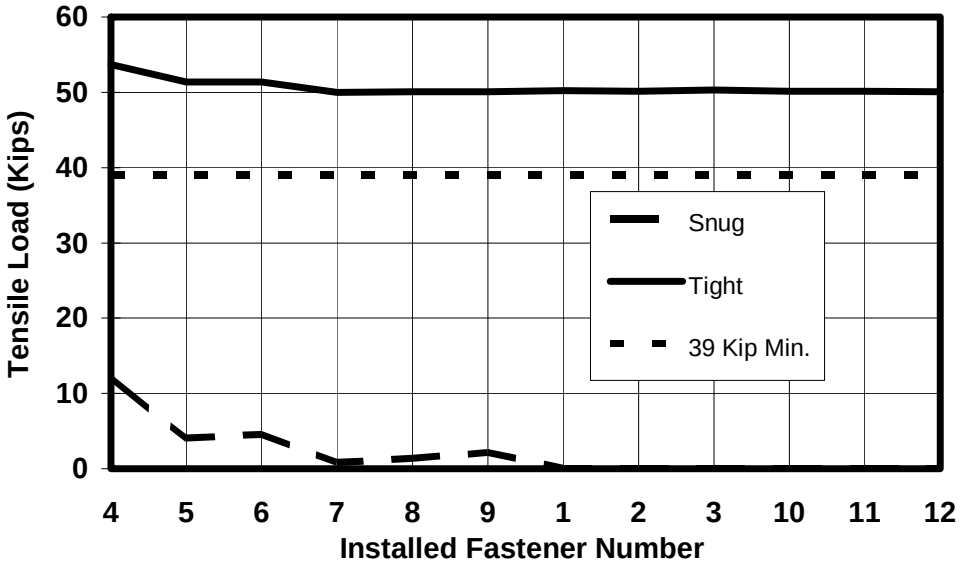


Figure B.8: **Tensile Load History for Fastener #4 - Test CD3TN123.MTO**

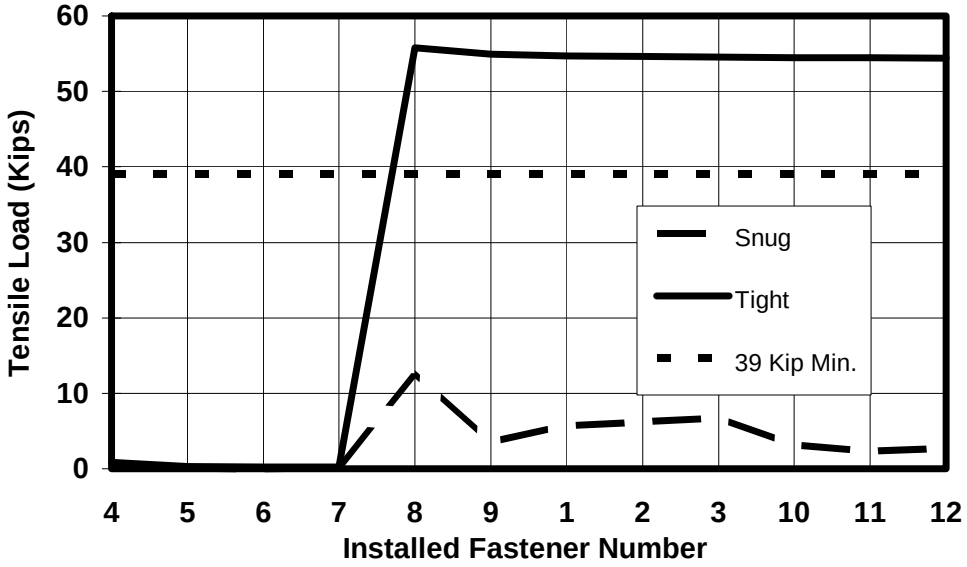


Figure B.9: **Tensile Load History for Fastener #8 - Test CD3TN123.MTO**

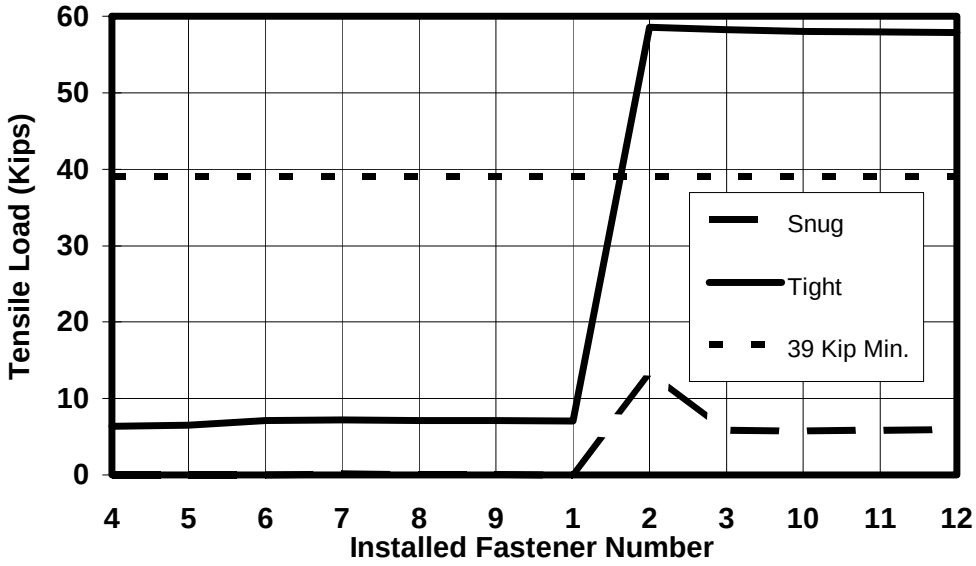


Figure B.10: **Tensile Load History for Fastener #2 - Test CD3TN123.MTO**

		Fastener Number											
		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	13.1	-0.1	0.0	0.0	-0.1	-0.1	-0.1	-0.1	0.0	0.1	2.0	0.0
	5	5.2	12.6	0.0	0.0	-0.1	-0.2	-0.1	0.0	0.0	0.1	2.3	-0.1
	6	5.4	3.8	12.6	0.0	-0.1	-0.2	-0.1	0.0	0.0	0.0	2.2	0.0
	7	0.9	1.7	11.0	14.4	-0.1	-0.2	-0.1	0.0	0.1	-0.1	-0.1	-0.1
	8	1.6	1.1	8.1	6.3	12.9	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	-0.1
	9	2.6	1.7	4.6	5.3	5.0	13.2	-0.1	-0.1	-0.1	-0.1	-0.2	-0.1
	1	-0.1	-0.2	0.8	7.5	6.9	16.5	13.7	-0.1	0.0	-0.1	-0.2	-0.2
	2	-0.1	-0.2	0.0	8.0	6.8	16.8	4.9	14.0	0.0	0.0	-0.2	-0.1
	3	-0.1	-0.3	-0.1	8.3	7.0	15.6	4.8	7.1	13.6	-0.1	-0.2	-0.2
	10	-0.1	-0.2	-0.1	1.0	3.1	13.5	6.2	7.8	14.1	14.1	-0.1	-0.1
	11	-0.1	-0.3	0.0	1.6	1.0	9.1	6.5	8.1	14.7	5.7	13.8	-0.1
	12	-0.1	-0.3	0.0	2.7	1.1	3.8	6.6	8.3	15.0	6.0	3.8	14.4
Tightening Order	4	36.6	-1.4	-1.1	-1.0	-1.2	0.1	1.3	4.7	13.6	4.8	2.3	13.5
	5	27.7	52.7	-1.1	-1.0	-1.3	-1.4	2.3	3.4	10.6	5.3	1.8	12.5
	6	28.0	48.2	40.0	-0.9	-1.2	-1.3	2.5	4.5	8.4	5.6	2.3	11.2
	7	23.1	46.7	39.3	52.3	-1.2	-1.3	2.9	4.7	8.5	0.3	0.5	11.2
	8	23.3	44.9	37.7	50.1	54.9	-1.3	3.0	4.8	8.6	0.1	-0.8	7.5
	9	23.4	45.0	32.6	50.3	52.7	56.9	3.0	5.0	9.2	0.3	-1.0	3.2
	1	23.5	45.2	32.7	50.1	52.5	56.4	59.7	2.7	8.8	0.3	-0.9	3.3
	2	23.8	45.4	33.0	50.2	52.5	56.4	59.1	58.9	6.5	0.4	-0.9	3.3
	3	23.8	45.5	32.9	50.0	52.4	56.4	59.1	58.0	56.4	0.3	-0.9	3.4
	10	23.9	45.5	33.0	49.3	52.1	56.4	59.1	58.3	56.3	53.7	-1.3	1.8
	11	23.9	45.5	33.0	49.4	51.8	56.2	59.1	58.3	56.2	53.1	55.8	-0.6
	12	23.9	45.4	33.2	49.5	52.0	55.6	59.0	58.3	56.3	53.1	54.4	59.0

Tension in Kips

Average Fastener Tension
(after snugging) = 5.1 Kips
(after tightening) = 50.0 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Middle to Outside

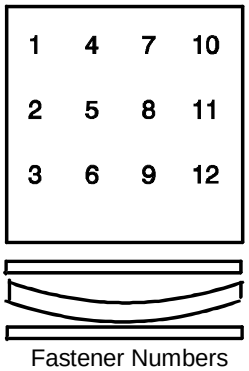


Figure B.11: Fastener Tensions for test CD3TN124.MTO

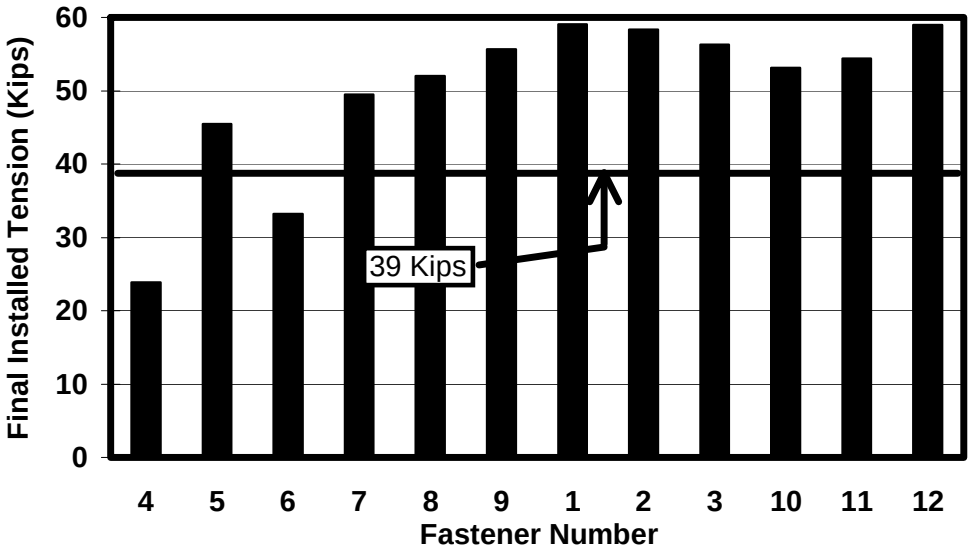


Figure B.12: **Final Installed Tensions for Test CD3TN124.MTO**

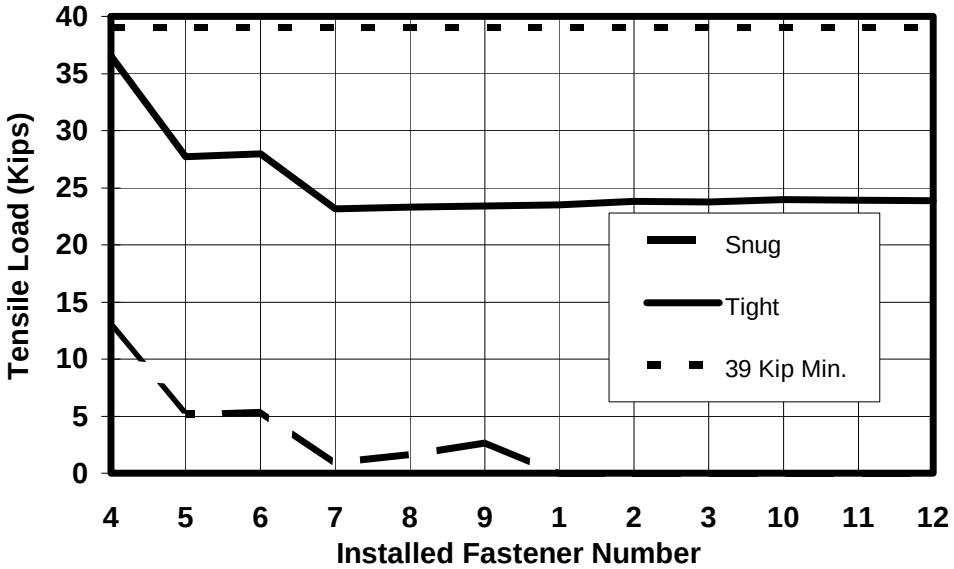


Figure B.13: **Tensile Load History for Fastener #4 - Test CD3TN124.MTO**

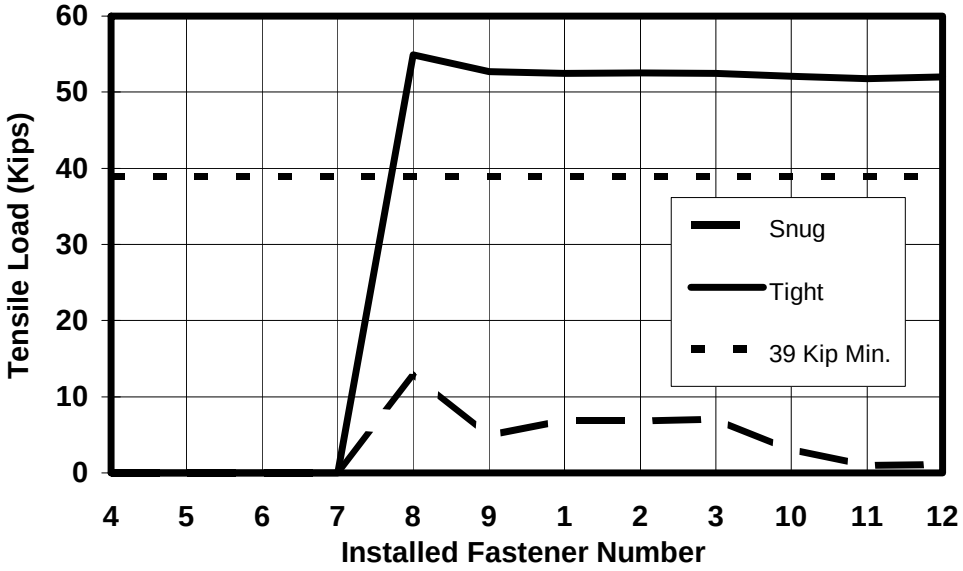


Figure B.14: **Tensile Load History for Fastener #8 - Test CD3TN124.MTO**

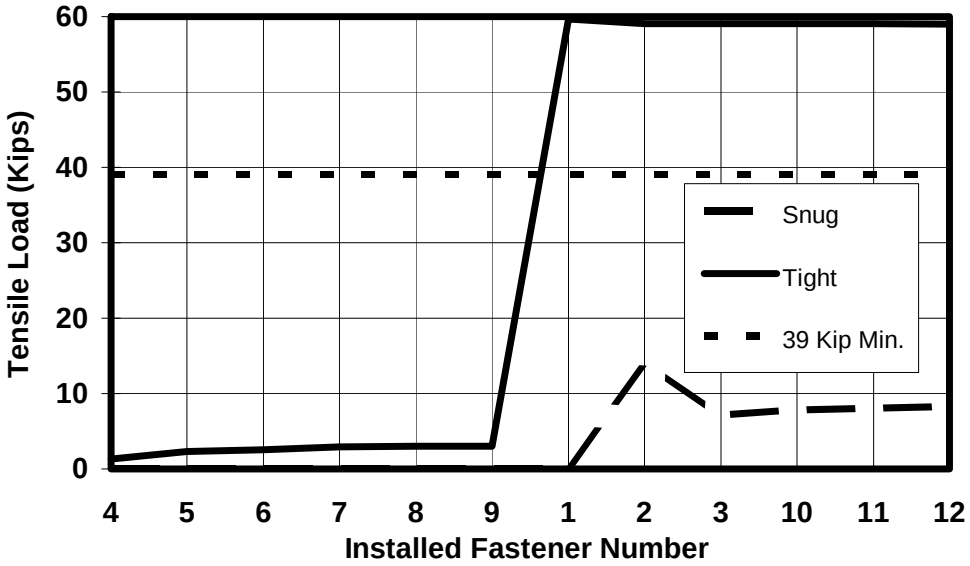


Figure B.15: **Tensile Load History for Fastener #2 - Test CD3TN124.MTO**

		Fastener Number											
		1	2	3	4	5	6	7	8	9	10	11	12
Snugging Order	1	12.1	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.0	0.5	0.6	0.0
	2	7.3	11.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.7	0.0
	3	7.5	8.7	12.4	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.0
	4	8.5	8.5	11.9	11.3	0.0	0.1	0.0	0.1	0.0	0.3	0.6	0.0
	5	8.9	9.4	10.4	7.8	12.5	0.2	0.1	0.1	0.2	0.4	0.3	0.1
	6	8.6	9.4	10.1	8.0	8.5	10.4	0.0	0.0	0.0	0.3	0.1	0.0
	7	8.6	9.4	10.0	5.1	7.0	9.7	12.8	0.0	0.0	0.0	0.0	0.0
	8	8.6	9.5	10.0	5.2	5.0	8.1	8.4	11.7	0.0	0.0	0.0	0.0
	9	8.6	9.5	10.2	5.4	5.1	5.0	8.4	7.1	11.0	0.0	0.0	0.0
	10	8.6	9.5	10.2	6.1	5.6	5.5	6.5	5.7	9.8	13.3	0.1	0.1
	11	8.9	9.6	10.3	6.2	5.8	5.9	6.8	5.9	9.2	13.7	12.7	0.2
	12	8.7	9.6	10.1	6.1	5.8	6.0	6.7	6.2	8.7	13.6	12.4	10.6
Tightening Order	1	57.2	9.6	9.9	5.4	5.6	5.8	6.6	6.0	8.1	13.1	11.8	10.0
	2	56.4	53.7	10.3	5.5	6.0	5.9	6.6	6.0	8.1	13.1	11.8	10.0
	3	56.4	53.1	53.0	5.5	6.1	6.4	6.7	6.1	8.1	13.1	11.9	10.1
	4	56.4	52.8	52.2	51.4	5.2	6.4	5.0	5.6	8.1	13.1	11.9	10.0
	5	56.4	52.8	52.1	50.6	53.4	5.9	5.1	4.5	7.8	13.1	11.9	10.1
	6	56.4	52.8	52.1	50.5	52.6	52.6	5.1	4.6	6.3	13.1	11.9	10.0
	7	56.3	52.7	52.0	50.4	52.4	51.8	52.6	4.2	6.4	13.5	12.0	10.0
	8	56.3	52.7	52.0	50.4	52.4	51.7	51.8	52.8	5.9	13.5	12.4	10.1
	9	56.3	52.7	51.9	50.3	52.4	51.6	51.6	51.9	51.3	13.5	12.4	10.7
	10	56.2	52.5	51.8	50.2	52.2	51.4	51.3	51.3	50.3	55.1	12.6	10.7
	11	56.3	52.6	51.8	50.2	52.2	51.4	51.2	51.3	50.2	54.6	51.1	10.9
	12	56.2	52.5	51.7	50.1	52.1	51.3	51.1	51.1	50.1	54.4	50.3	53.8

Tension in Kips

Average Fastener Tension
(after snugging) = 8.7 Kips
(after tightening) = 52.1 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Top Left to Bottom Right

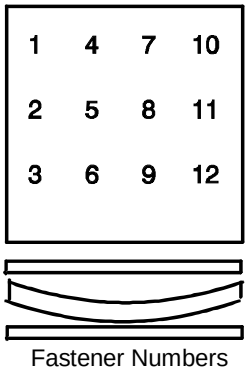


Figure B.16: Fastener Tensions for test CD3TN122.LTR

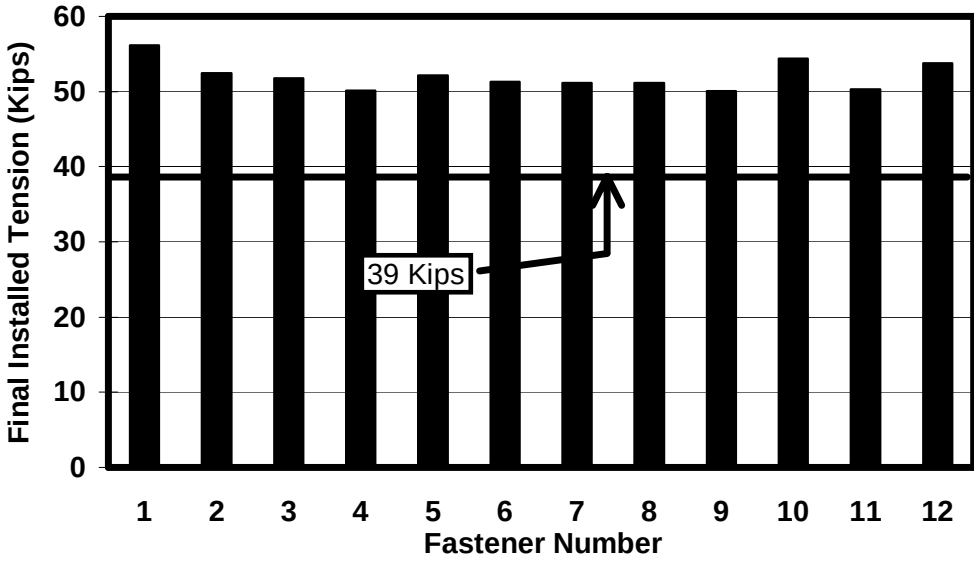


Figure B.17: **Final Installed Tensions for Test CD3TN122.LTR**

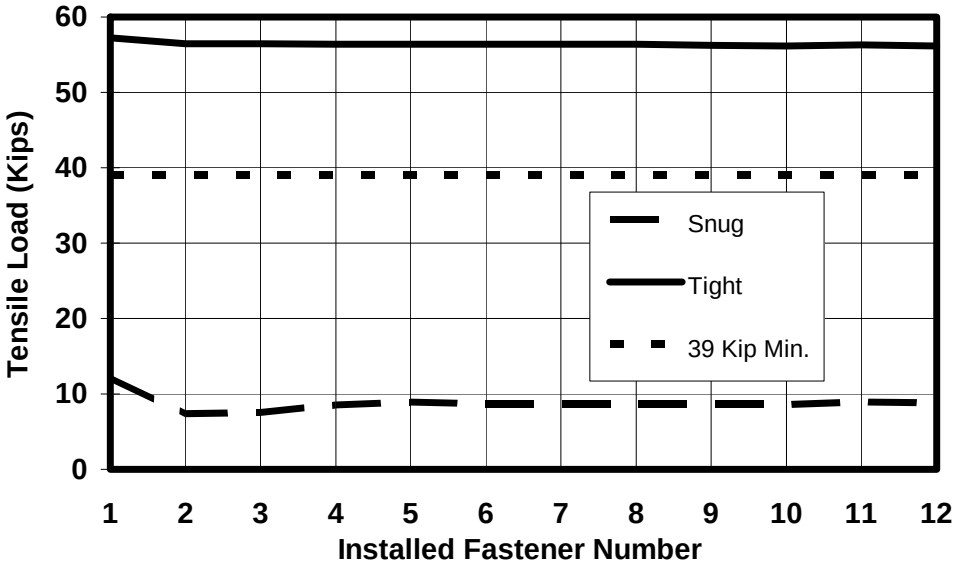


Figure B.18: **Tensile Load History for Fastener #1 - Test CD3TN122.LTR**

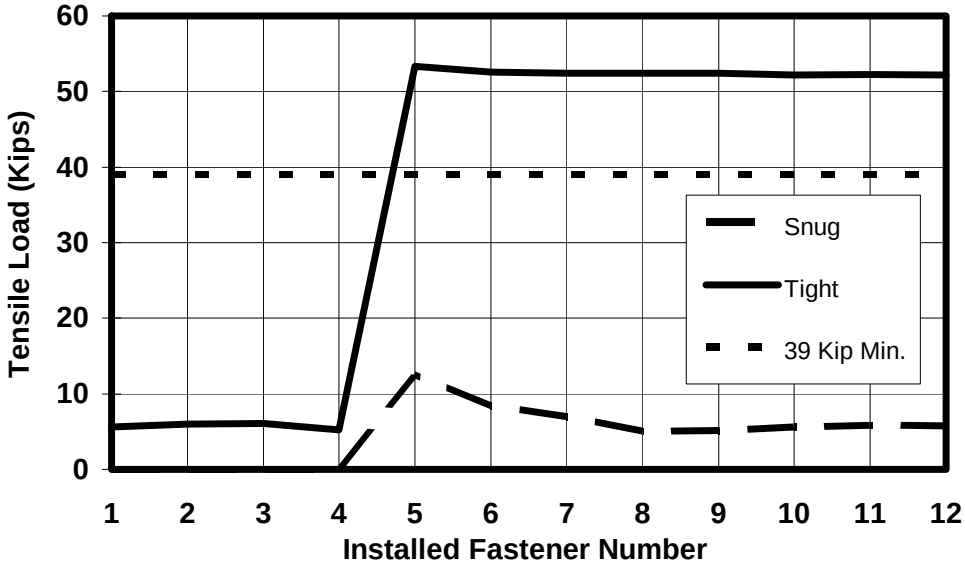


Figure B.19: **Tensile Load History for Fastener #5 - Test CD3TN122.LTR**

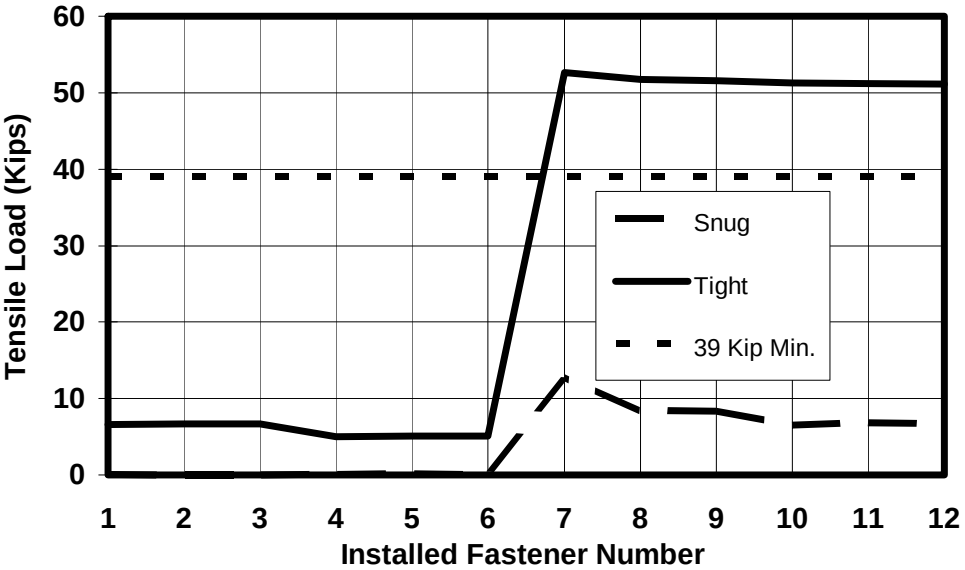


Figure B.20: **Tensile Load History for Fastener #7 - Test CD3TN122.LTR**

		Fastener Number											
		1	2	3	4	5	6	7	8	9	10	11	12
Snugging Order	1	11.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.8	1.5
	2	6.7	11.7	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.6	2.3	2.0
	3	6.8	5.9	12.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.6	2.6	2.4
	4	2.9	2.8	9.4	11.6	0.0	0.0	0.0	0.0	-0.1	0.1	2.1	2.9
	5	2.8	1.7	7.8	4.7	12.1	0.0	0.0	0.0	-0.1	0.0	1.6	2.0
	6	3.1	1.8	5.4	4.9	5.1	12.0	0.0	0.0	-0.1	0.2	1.5	1.1
	7	3.6	2.0	6.2	0.0	1.4	10.6	10.3	0.0	-0.2	-0.1	-0.1	0.0
	8	4.1	2.1	7.4	0.0	0.4	6.1	5.1	12.2	-0.1	0.0	0.0	0.0
	9	4.1	2.4	8.2	0.1	0.3	1.5	6.3	4.3	11.2	0.0	-0.1	-0.1
	10	5.0	2.5	8.8	1.4	1.5	4.0	0.0	0.3	6.6	13.1	-0.1	-0.1
	11	4.9	2.4	9.5	1.9	1.8	5.2	0.0	0.0	2.5	5.8	10.7	0.0
	12	4.7	2.6	10.7	2.3	2.1	4.6	0.3	0.0	0.1	7.1	1.5	12.7
Tightening Order	1	54.9	1.2	11.2	0.3	1.3	4.8	0.1	0.0	0.0	6.9	1.6	12.2
	2	54.6	58.4	8.0	0.3	0.5	4.0	0.1	0.0	-0.1	6.9	1.6	12.1
	3	54.4	58.5	57.4	0.3	0.4	0.7	0.1	0.0	-0.3	6.9	1.6	12.1
	4	54.4	58.3	56.7	56.7	0.0	0.2	0.0	0.0	-0.4	5.4	1.6	12.3
	5	54.3	58.0	55.4	53.7	56.0	-0.1	0.0	0.0	-0.5	5.8	1.6	11.7
	6	54.3	58.2	55.6	53.8	53.8	58.1	0.1	0.0	-0.5	6.0	2.0	11.0
	7	54.2	58.1	55.5	52.6	53.5	57.3	57.6	0.0	-0.5	0.3	0.8	11.1
	8	54.1	58.0	55.3	52.7	52.4	56.5	56.4	57.1	-0.6	0.1	0.0	8.5
	9	54.0	58.0	55.4	52.6	52.5	54.1	56.3	56.3	53.1	0.4	0.0	4.2
	10	54.0	58.0	55.4	52.6	52.4	54.1	55.9	56.0	52.5	58.1	0.1	3.2
	11	54.1	58.0	55.3	52.6	52.4	54.1	55.9	55.9	52.1	57.6	54.3	1.6
	12	54.1	58.0	55.3	52.6	52.4	54.1	55.9	56.0	51.8	57.5	53.8	57.9

Tension in Kips

Average Fastener Tension
(after snugging) = 4.1 Kips
(after tightening) = 55.0 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Top Left to Bottom Right

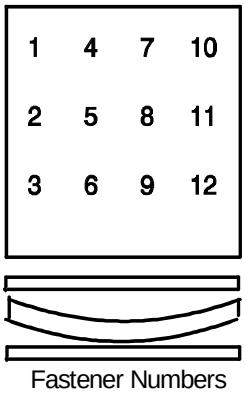


Figure B.21: Fastener Tensions for test CD3TN123.LTR

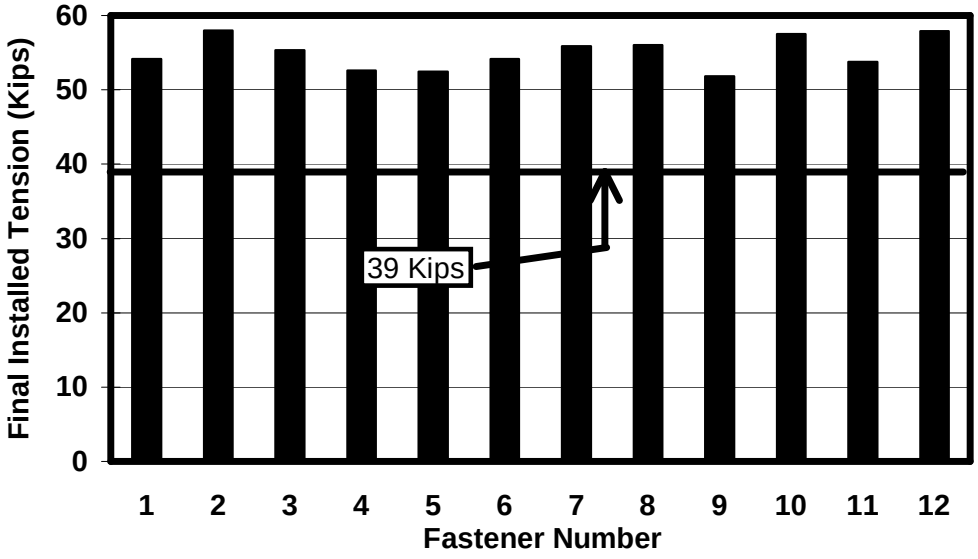


Figure B.22: Final Installed Tensions for Test CD3TN123.LTR

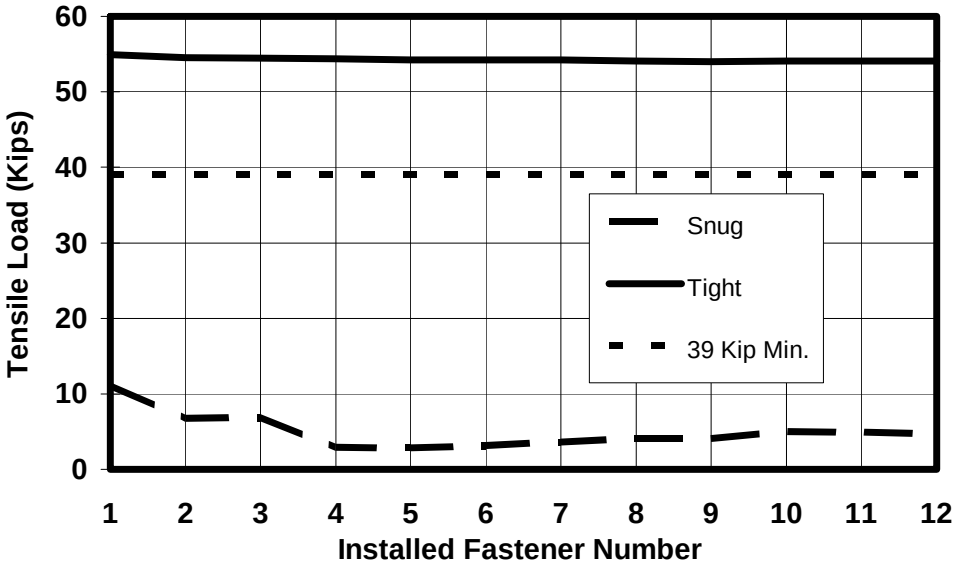


Figure B.23: Tensile Load History for Fastener #1 - Test CD3TN123.LTR

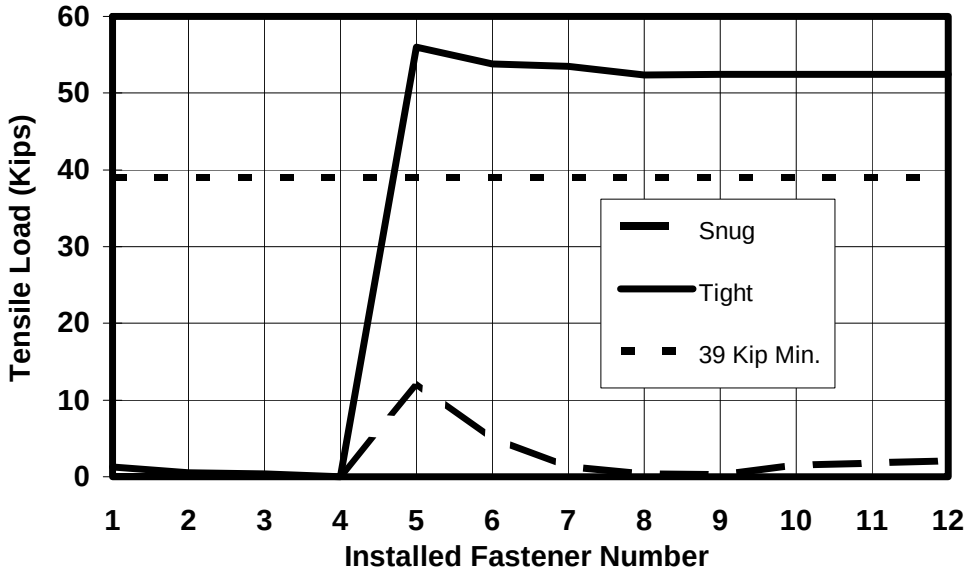


Figure B.24: **Tensile Load History for Fastener #5 - Test CD3TN123.LTR**

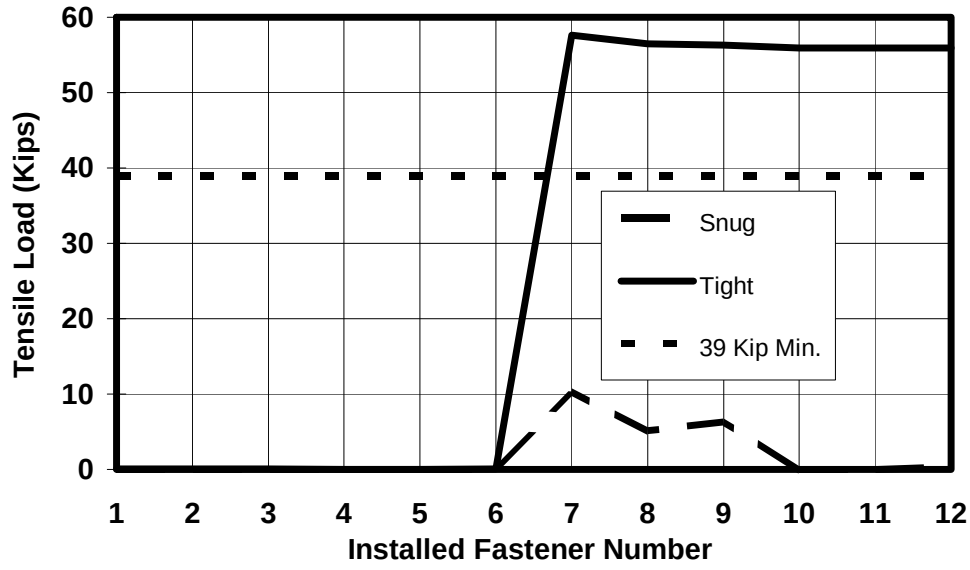


Figure B.25: **Tensile Load History for Fastener #7 - Test CD3TN123.LTR**

		Fastener Number											
		1	2	3	4	5	6	7	8	9	10	11	12
Snugging Order	1	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.2	1.7
	2	8.2	11.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.2	2.2
	3	8.0	6.4	10.7	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.3	2.2
	4	2.6	4.0	9.4	12.2	0.0	0.0	0.0	0.0	0.0	0.1	0.0	1.6
	5	2.3	2.7	6.8	4.9	13.4	0.0	0.0	0.0	-2.0	0.0	0.0	0.6
	6	2.8	2.9	3.7	4.7	5.9	10.8	0.0	0.0	-2.0	0.0	0.0	0.0
	7	2.8	4.1	5.7	0.1	2.0	8.3	11.8	0.0	-2.0	0.0	0.0	0.0
	8	3.2	4.3	6.7	0.1	0.9	4.2	5.8	10.9	-1.9	0.0	0.0	0.0
	9	3.5	5.1	6.8	0.2	0.7	1.0	6.0	4.4	9.2	0.0	0.0	0.0
	10	5.0	5.9	8.2	1.0	1.6	2.5	0.2	1.1	6.1	12.0	0.0	0.0
	11	5.2	6.2	9.6	1.4	1.9	3.4	0.3	0.0	1.5	4.1	12.6	0.0
	12	5.2	6.6	10.7	1.7	2.0	3.0	0.5	0.0	-1.3	4.7	4.2	10.9
Tightening Order	1	56.9	0.6	9.1	-0.4	0.1	1.8	-0.2	-0.1	-1.4	4.5	3.9	10.5
	2	52.2	58.0	1.5	-0.3	-0.1	0.1	-0.1	-0.1	-1.1	4.3	3.4	10.7
	3	51.8	53.5	56.9	-0.3	-0.1	-0.2	-0.1	-0.1	-1.1	4.5	3.5	9.1
	4	48.5	51.7	55.4	42.5	-0.1	-0.2	-0.1	-0.1	-1.0	3.4	3.0	9.4
	5	49.0	51.7	53.2	35.0	51.8	-0.2	-0.1	-0.1	-1.0	3.6	2.4	8.5
	6	49.0	52.4	51.8	34.8	45.8	52.8	-0.1	-0.1	-1.0	4.0	2.5	6.6
	7	49.2	52.5	51.9	29.9	44.2	52.1	34.6	-0.1	-1.0	-0.1	0.6	6.2
	8	49.2	52.6	52.0	30.3	42.1	50.0	25.4	56.0	-0.9	-0.1	-0.1	1.2
	9	49.2	52.6	52.3	30.6	42.6	45.0	24.2	47.4	48.4	-0.1	-0.1	-0.1
	10	49.1	52.6	52.2	31.2	42.7	45.2	18.3	43.5	45.4	26.9	-0.1	-0.1
	11	49.1	52.6	52.2	31.2	42.7	45.2	19.0	43.1	44.0	25.4	53.3	-0.1
	12	49.1	52.6	52.2	31.2	42.8	45.3	19.1	43.4	43.9	25.5	51.8	48.2

Tension in Kips

Average Fastener Tension
(after snugging) = 4.0 Kips
(after tightening) = 42.1 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Top Left to Bottom Right

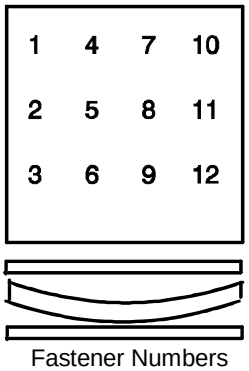


Figure B.26: Fastener Tensions for test CD3TN124.LTR

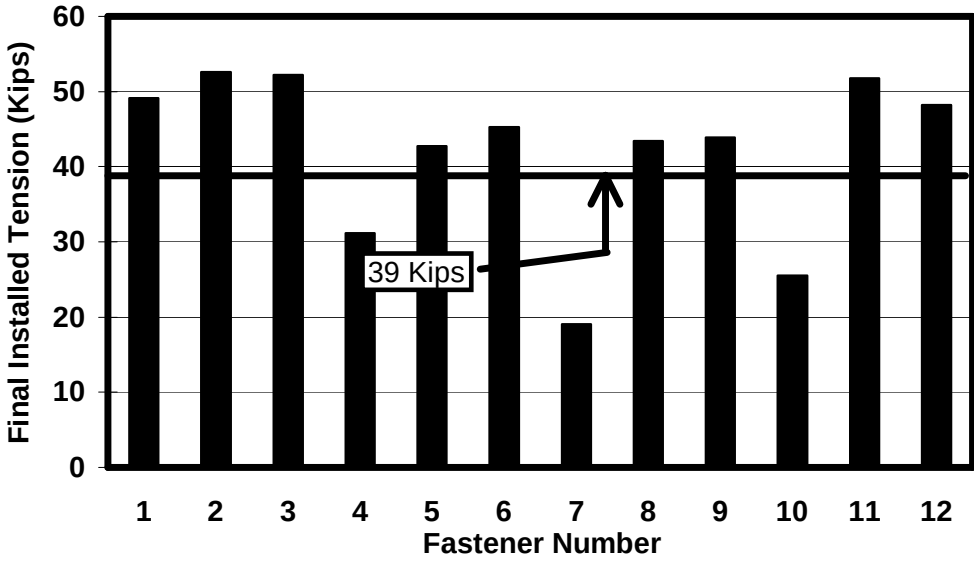


Figure B.27: **Final Installed Tensions for Test CD3TN124.LTR**

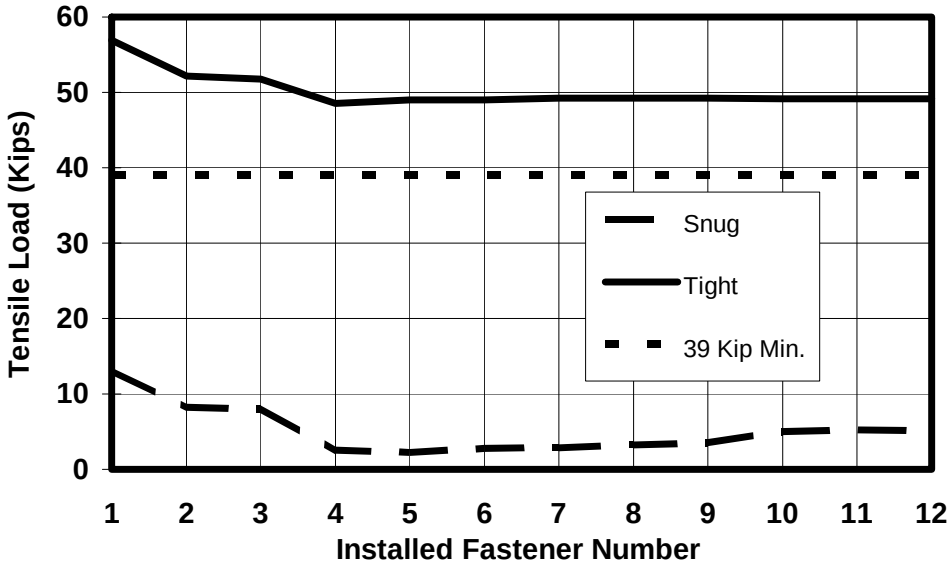


Figure B.28: **Tensile Load History for Fastener #1 - Test CD3TN124.LTR**

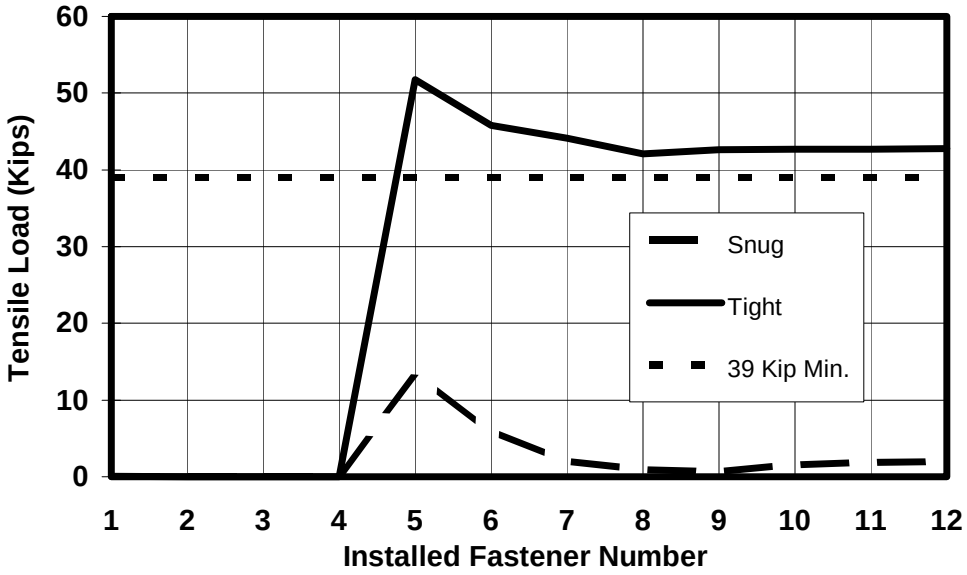


Figure B.29: **Tensile Load History for Fastener #5 - Test CD3TN124.LTR**

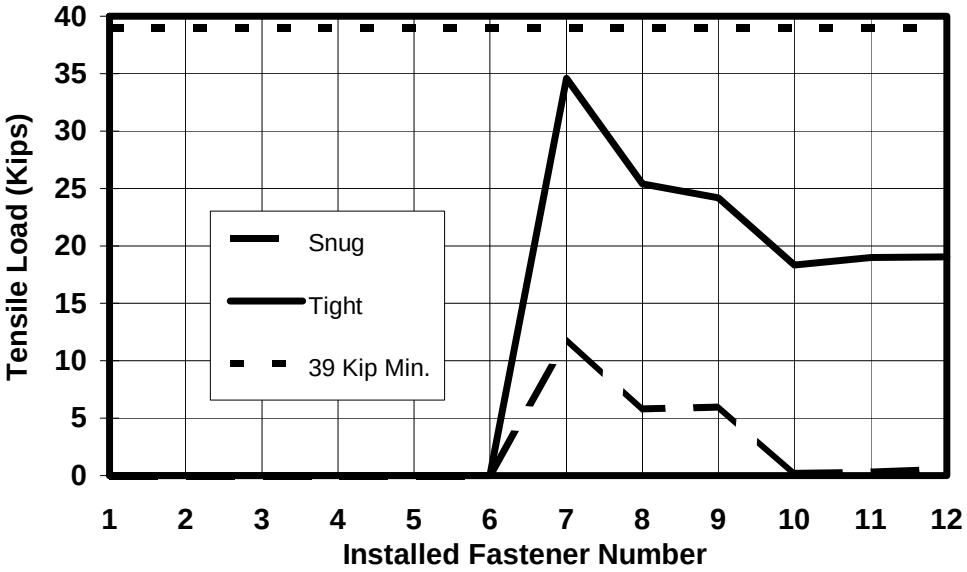


Figure B.30: **Tensile Load History for Fastener #7 - CD3TN124.LTR**

		Fastener Number											
		1	2	3	10	11	12	4	5	6	7	8	9
Snugging Order	1	11.4	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	2	6.8	11.1	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0
	3	6.3	6.1	11.3	0.0	0.0	-0.1	-0.1	-0.1	0.0	-0.1	-0.1	0.0
	10	5.3	5.3	9.3	14.4	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
	11	5.4	5.1	8.2	12.5	10.7	-0.1	-0.1	-0.1	-0.1	0.0	-0.1	-0.1
	12	5.4	5.0	6.8	12.4	7.5	10.4	-0.1	-0.1	-0.2	-0.1	-0.1	-0.1
	4	6.2	5.0	6.8	12.0	7.1	10.0	10.9	-0.1	-0.2	-0.1	-0.1	-0.1
	5	6.4	5.1	6.3	12.0	6.8	9.2	8.5	7.8	-0.2	-0.1	-0.1	-0.1
	6	6.4	5.3	5.8	12.1	6.9	8.6	8.8	4.7	11.6	-0.1	-0.1	-0.1
	7	6.4	5.3	5.8	12.6	6.9	8.6	5.5	3.9	11.4	11.0	-0.1	-0.1
	8	6.4	5.4	5.8	12.8	7.1	8.8	5.2	2.6	10.0	9.0	11.4	-0.1
	9	6.4	5.5	6.0	12.7	7.3	9.3	5.3	2.5	6.6	9.0	9.6	11.7
Tightening Order	1	43.1	5.7	5.9	12.6	7.2	9.1	5.8	2.6	BG	8.8	9.3	11.1
	2	43.1	54.8	6.5	12.6	7.2	9.1	5.9	2.9	BG	8.8	9.4	11.1
	3	43.1	54.0	52.3	12.6	7.2	9.2	5.9	2.9	BG	8.8	9.4	11.2
	10	43.1	53.8	51.8	52.9	7.6	9.2	5.9	2.9	BG	9.2	9.5	11.2
	11	43.1	53.5	51.4	52.1	55.0	9.6	5.9	2.9	BG	9.2	9.9	11.2
	12	43.1	53.5	51.3	52.1	54.5	54.4	5.9	2.9	BG	9.2	10.0	11.7
	4	43.1	53.5	51.2	52.0	54.2	53.6	54.6	2.3	BG	7.3	9.4	11.8
	5	43.1	53.5	51.1	51.9	54.0	53.5	53.7	49.4	BG	7.4	7.9	11.5
	6	43.1	53.4	51.2	51.8	54.0	53.4	53.5	48.9	BG	7.5	8.1	9.9
	7	43.1	53.4	51.1	51.8	53.9	53.4	53.4	48.8	BG	53.6	7.5	10.0
	8	43.0	53.4	51.0	51.7	53.9	53.3	53.4	48.8	BG	53.0	55.3	9.7
	9	43.0	53.4	51.0	51.7	53.9	53.4	53.4	48.8	BG	52.8	54.5	53.4

Tension in Kips

Average Fastener Tension
(after snugging) = 7.7 Kips
(after tightening) = 51.8 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Outside to Middle

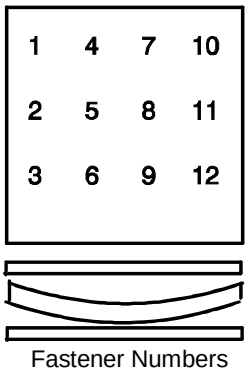


Figure B.31: Fastener Tensions for test CD3TN122.OTM

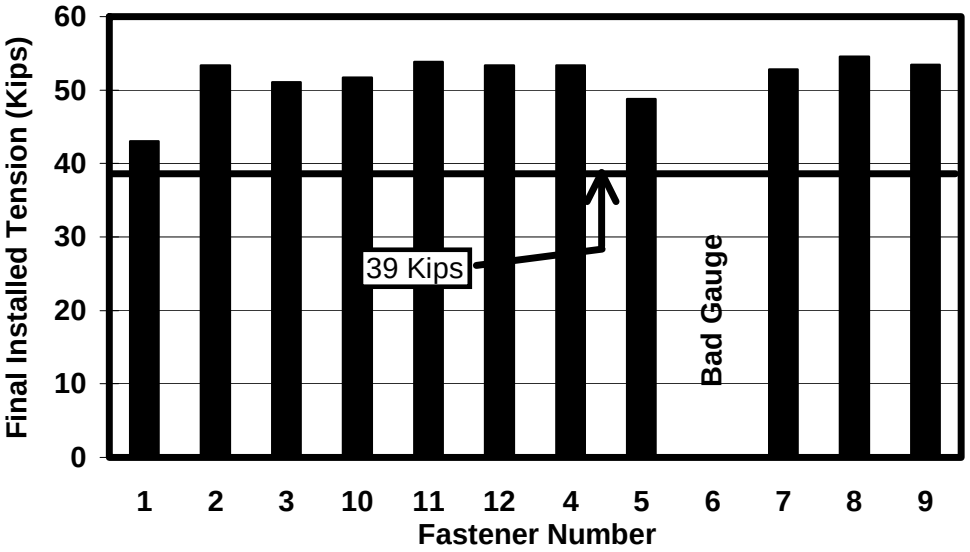


Figure B.32: **Final Installed Tensions for Test CD3TN122.OTM**

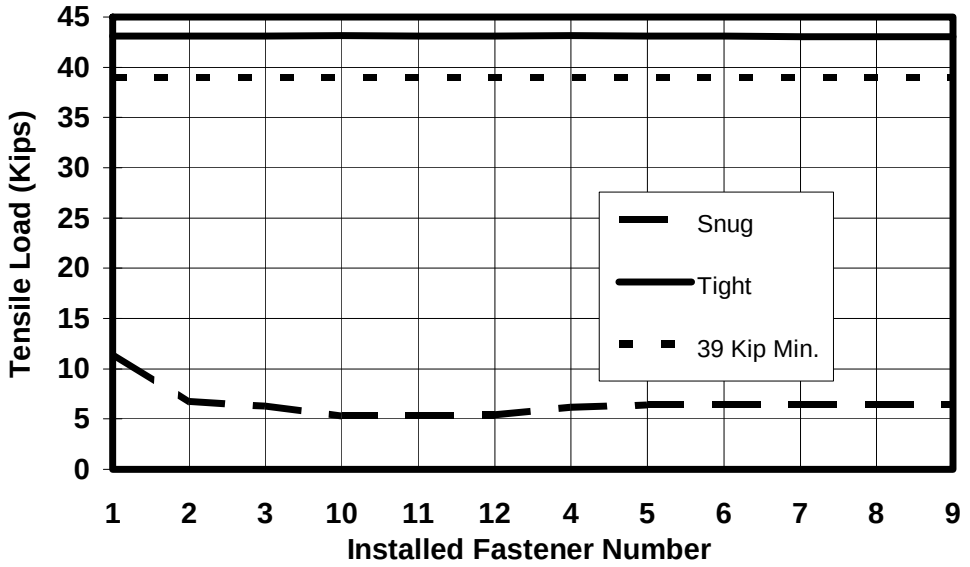


Figure B.33: **Tensile Load History for Fastener #1 - Test CD3TN122.OTM**

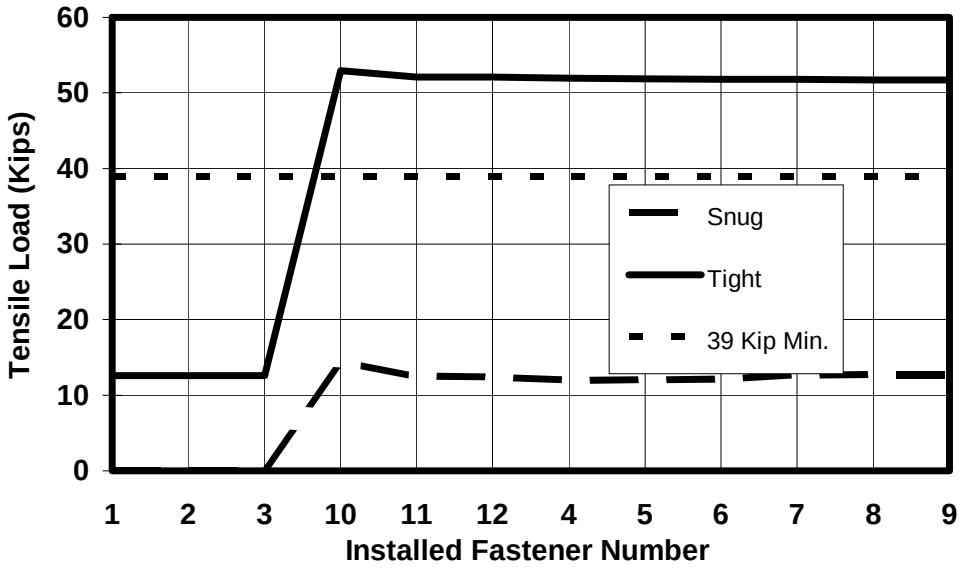


Figure B.34: **Tensile Load History for Fastener #10 - Test CD3TN122.OTM**

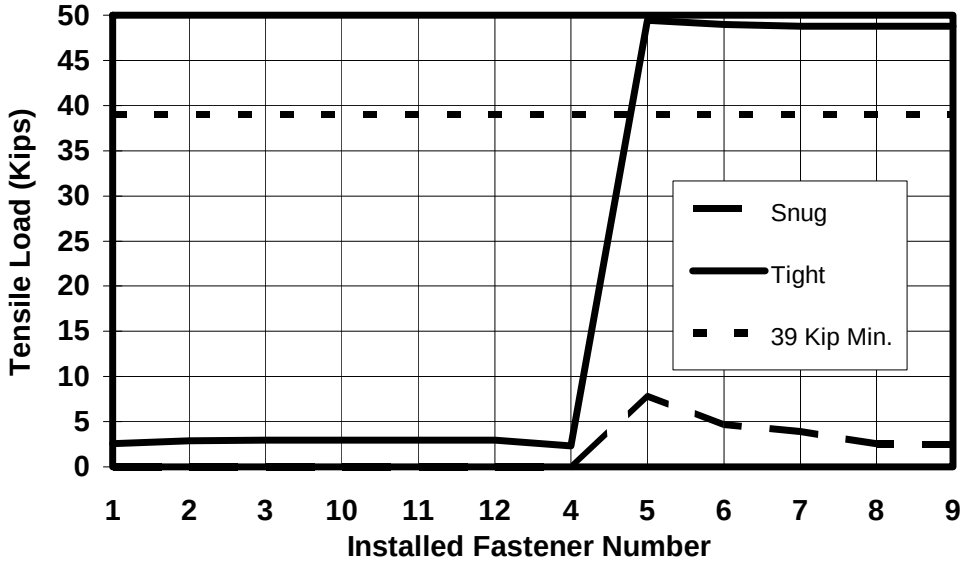


Figure B.35: **Tensile Load History for Fastener #5 - Test CD3TN122.OTM**

Fastener Number

		1	2	3	10	11	12	4	5	6	7	8	9
Snugging Order	1	13.3	0.1	0.0	2.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0
	2	8.8	9.6	0.0	2.4	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0
	3	8.6	5.2	13.4	2.6	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0
	10	7.7	4.5	11.9	10.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11	7.7	4.2	11.5	1.0	12.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	12	7.5	4.2	11.2	2.5	1.5	12.2	0.0	0.0	0.0	0.0	0.0	0.0
	4	3.1	3.3	10.1	1.9	1.5	11.9	10.9	0.0	0.0	0.0	0.0	0.0
	5	3.5	2.5	8.4	2.1	1.3	11.3	4.6	12.0	0.0	0.0	0.1	0.0
	6	3.7	2.6	6.0	2.3	1.6	10.6	4.7	6.6	9.9	0.0	0.0	0.0
	7	4.7	2.8	6.2	0.0	0.4	10.7	1.1	4.0	8.7	11.9	0.0	0.0
	8	4.9	2.9	6.5	0.0	0.0	9.0	0.8	2.6	6.3	8.4	11.6	0.0
	9	4.9	3.3	6.8	0.0	0.3	6.7	0.9	2.3	3.2	8.9	8.7	10.9
Tightening Order	1	57.9	2.2	7.3	0.0	0.3	6.9	0.6	2.6	3.5	9.1	8.7	10.3
	2	57.4	56.5	5.5	0.0	0.3	7.0	0.7	2.1	3.5	9.2	8.8	10.4
	3	57.3	56.8	59.4	0.1	0.4	7.2	0.8	2.5	2.4	9.3	8.9	10.5
	10	57.0	56.3	58.5	25.2	0.0	3.0	1.4	3.0	2.7	3.8	5.7	11.1
	11	56.9	56.1	58.3	24.7	56.8	0.2	1.5	3.2	2.9	4.3	4.6	9.9
	12	56.8	56.1	58.3	24.7	56.2	55.0	1.5	3.4	2.8	4.5	5.0	5.9
	4	57.1	56.3	58.2	24.7	56.2	54.4	59.7	1.6	2.7	0.9	3.0	6.0
	5	57.1	56.2	58.1	24.7	56.1	54.2	58.3	56.4	1.3	0.7	1.1	4.3
	6	57.1	56.4	58.2	24.7	56.1	54.1	58.3	55.2	54.3	0.8	1.1	1.6
	7	57.1	56.3	58.2	24.8	56.2	54.0	57.2	54.9	53.8	55.6	0.7	1.6
	8	57.0	56.2	58.1	24.9	56.3	54.0	57.2	53.8	53.2	55.0	58.4	1.3
	9	57.0	56.2	58.1	24.9	56.3	54.2	57.2	53.9	50.7	54.8	57.7	57.2

Tension in Kips

Average Fastener Tension
(after snugging) = 4.7 Kips
(after tightening) = 53.2 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Outside to Middle

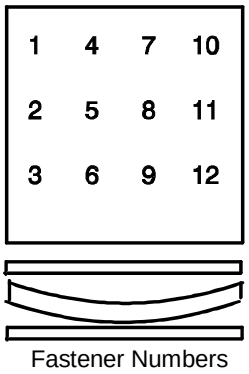


Figure B.36: Fastener Tensions for test CD3TN123.OTM

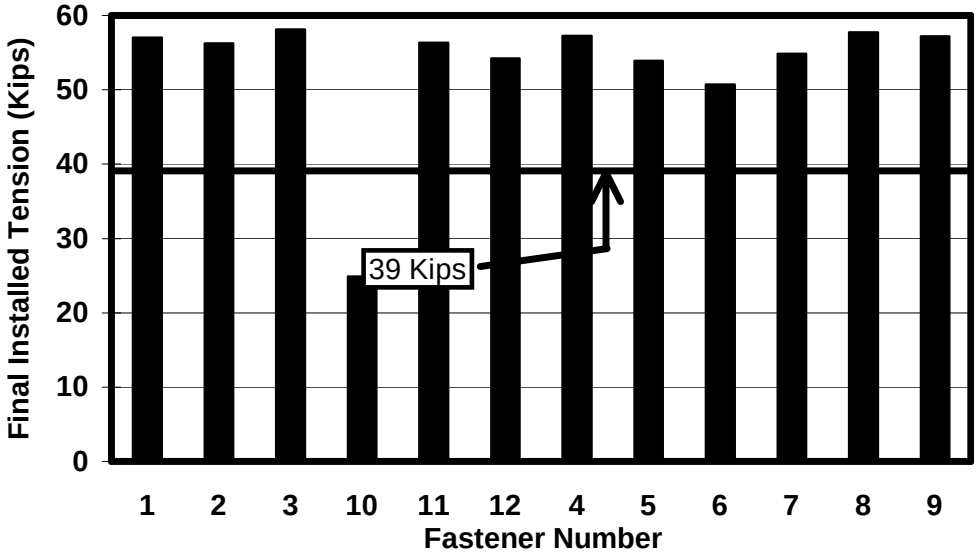


Figure B.37: Final Installed Tensions for Test CD3TN123.OTM

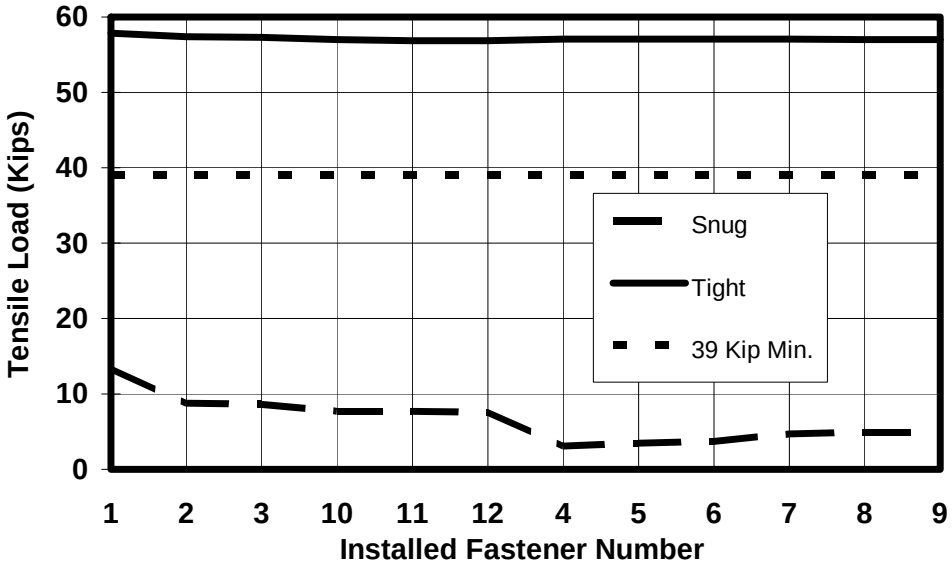


Figure B.38: Tensile Load History for Fastener #1 - Test CD3TN123.OTM

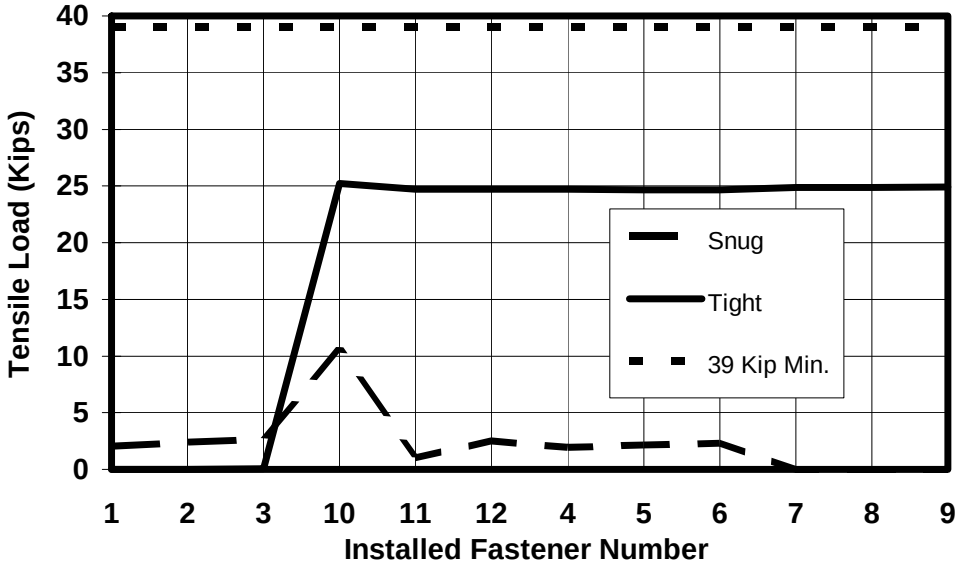


Figure B.39: **Tensile Load History for Fastener #10 - Test CD3TN123.OTM**

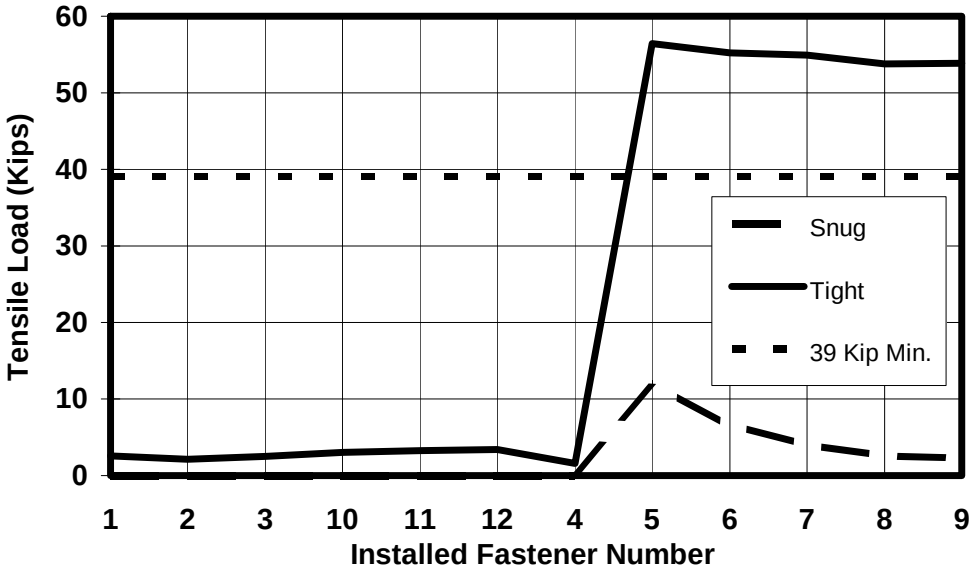


Figure B.40: **Tensile Load History for Fastener #5 - Test CD3TN123.OTM**

		Fastener Number											
		1	2	3	10	11	12	4	5	6	7	8	9
Snugging Order	1	12.1	0.0	0.0	0.2	0.1	1.8	0.0	0.0	0.0	0.0	0.0	0.0
	2	7.2	13.1	0.0	0.2	0.1	2.3	0.0	0.0	0.1	0.0	0.0	0.0
	3	7.0	7.8	12.1	0.2	0.0	2.5	0.0	-0.1	0.0	0.0	0.0	0.0
	10	5.5	7.5	13.0	11.5	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
	11	5.8	7.3	13.0	2.9	12.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	12	6.0	7.6	12.5	3.7	2.4	11.0	-0.1	-0.1	-0.1	-0.1	0.0	-0.1
	4	2.6	5.6	12.1	2.5	2.0	10.4	11.7	-0.1	0.0	0.0	0.0	0.0
	5	2.9	4.1	10.4	2.5	1.7	9.4	6.1	11.3	0.0	0.0	0.0	0.0
	6	3.4	4.3	7.5	2.7	1.9	7.8	5.6	5.1	9.9	0.0	0.0	0.0
	7	3.8	4.9	8.0	0.7	0.8	7.8	1.5	2.6	8.3	11.4	0.0	-0.1
	8	4.0	5.0	8.4	0.7	0.2	6.0	1.0	1.3	6.1	7.1	11.0	-0.1
	9	4.2	5.5	8.4	0.9	0.2	3.1	1.0	0.8	2.6	7.2	6.1	12.8
Tightening Order	1	58.0	0.5	6.9	1.5	0.5	3.6	0.2	0.3	2.5	4.8	5.0	12.1
	2	55.7	57.8	1.8	1.6	0.6	4.2	0.2	0.0	1.1	4.1	3.8	11.1
	3	55.8	56.0	57.1	1.7	0.8	4.8	0.2	0.0	0.0	4.3	3.6	7.4
	10	55.7	55.9	56.7	15.6	0.0	1.1	0.1	0.0	0.1	0.1	0.8	7.7
	11	55.6	55.7	56.5	1.4	25.5	-0.1	0.1	-0.2	0.4	0.1	-0.1	1.3
	12	55.7	55.7	55.6	2.1	7.4	28.6	0.2	-0.2	0.1	0.5	-0.1	-0.1
	4	54.3	55.2	55.5	1.6	6.4	27.8	49.2	-0.2	0.0	0.0	0.0	0.0
	5	54.7	55.2	54.6	1.7	5.9	26.5	43.5	56.2	-0.1	-0.1	-0.1	0.0
	6	54.7	55.6	53.9	1.7	6.3	25.2	43.6	52.3	49.2	-0.1	-0.1	-0.1
	7	54.8	55.7	53.9	0.0	2.6	24.4	39.1	51.0	48.6	48.3	-0.2	-0.1
	8	54.8	55.7	53.9	0.0	1.6	22.9	39.1	49.2	47.3	45.9	54.5	-0.1
	9	54.9	55.8	54.1	0.0	1.9	22.6	39.2	49.2	43.2	46.0	53.1	54.6

Tension in Kips

Average Fastener Tension
(after snugging) = 4.4 Kips
(after tightening) = 39.5 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Outside to Middle

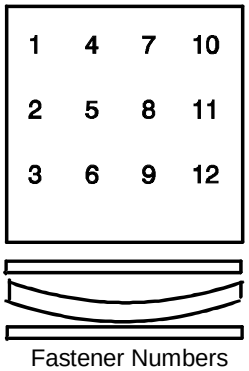


Figure B.41: Fastener Tensions for test CD3TN124.OTM

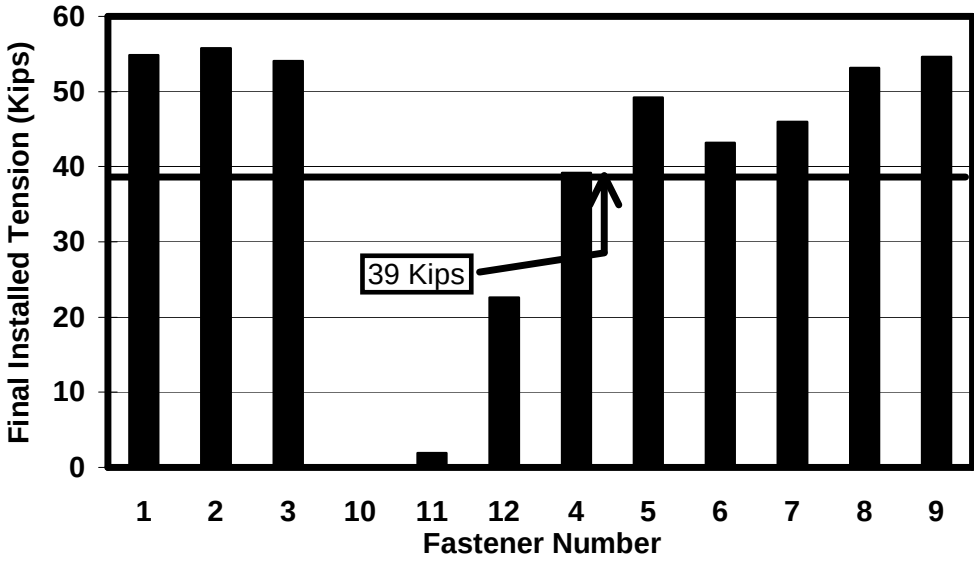


Figure B.42: **Final Installed Tensions for Test CD3TN124.OTM**

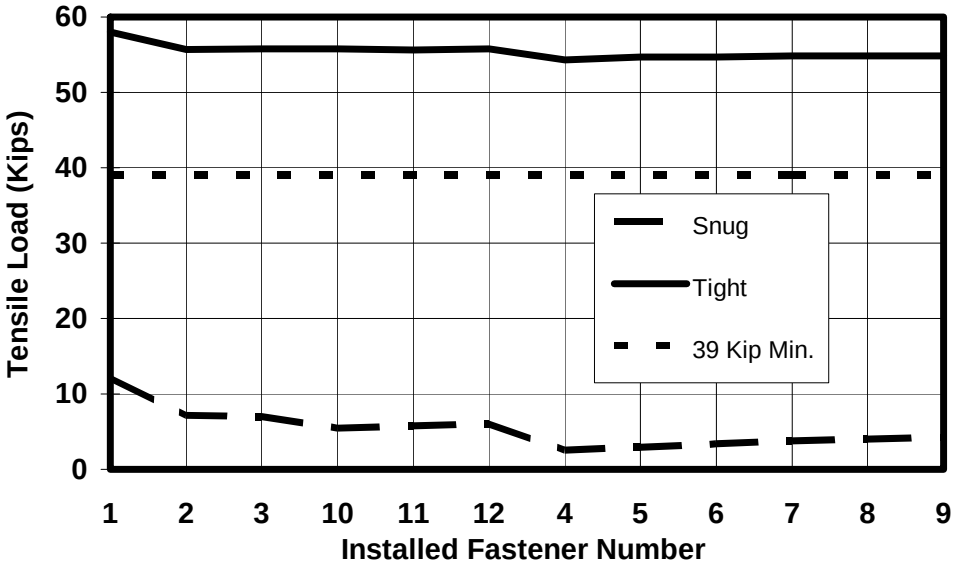


Figure B.43: **Tensile Load History for Fastener #1 - Test CD3TN124.OTM**

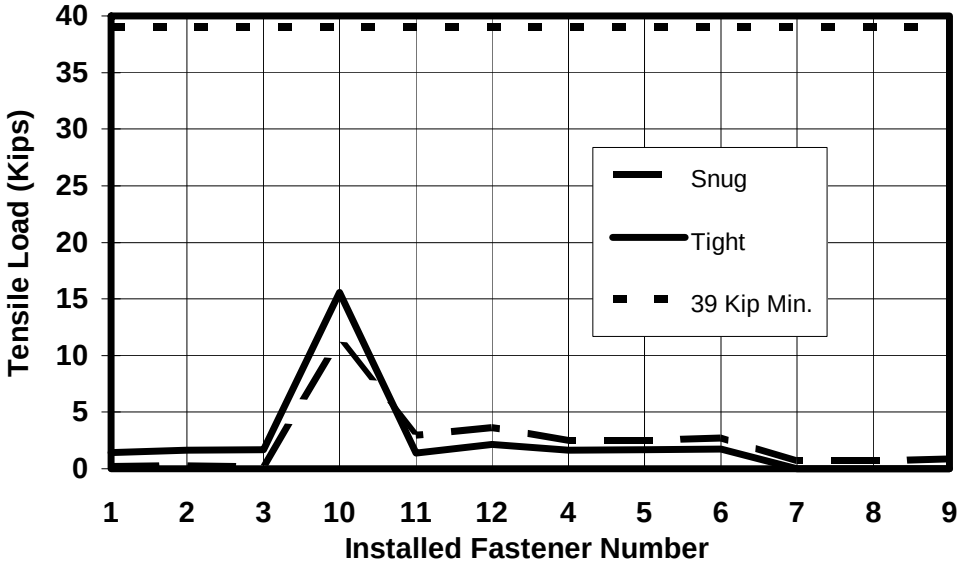


Figure B.44: **Tensile Load History for Fastener #10 - Test CD3TN124.OTM**

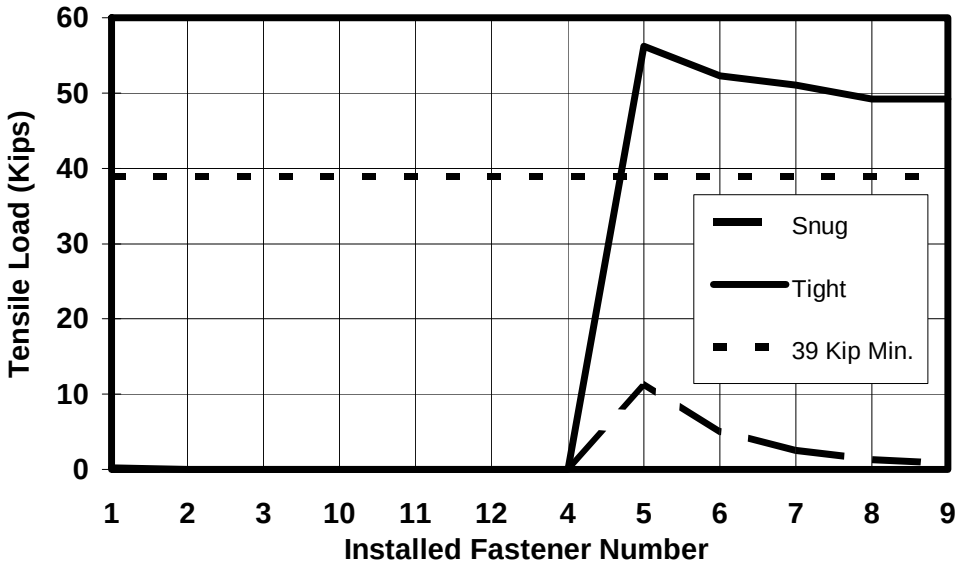


Figure B.45: **Tensile Load History for Fastener #5 - Test CD3TN124.OTM**

Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	24.5	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.7
	5	18.0	22.2	0.0	0.0	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.4
	6	18.1	19.3	25.6	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.4
	7	18.2	19.2	25.3	24.5	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.1
	8	18.2	19.4	25.3	20.1	25.4	-0.1	-0.1	0.0	0.0	-0.1	-0.1	-0.1
	9	18.2	19.6	25.4	19.9	21.9	23.2	0.0	0.0	-0.1	0.0	-0.1	-0.1
	1	18.4	19.4	25.0	20.0	21.9	22.7	23.7	0.1	0.1	0.1	0.1	0.1
	2	18.5	19.7	24.7	20.0	22.0	22.8	23.6	23.6	0.1	0.2	0.1	0.2
	3	18.5	19.8	25.0	19.9	21.9	22.7	23.5	23.6	21.6	0.1	0.1	0.1
	10	18.5	19.8	25.1	18.5	21.3	22.4	23.4	23.5	21.3	27.4	0.1	0.2
	11	18.5	19.8	25.1	18.6	21.4	22.0	23.4	23.5	21.2	27.5	27.6	0.2
	12	18.5	19.9	25.1	18.7	21.5	22.3	23.4	23.5	21.2	27.4	27.5	22.4
Tightening Order	4	45.1	19.9	25.0	18.7	21.5	22.2	23.0	23.2	20.8	27.0	27.0	21.5
	5	44.6	39.4	25.0	18.7	21.5	22.2	23.0	23.2	20.8	27.0	27.0	21.5
	6	44.6	39.2	41.7	18.8	21.6	22.2	23.0	23.2	20.8	27.0	27.0	21.5
	7	44.5	39.1	41.4	42.2	21.5	22.2	23.0	23.2	20.8	27.0	27.0	21.5
	8	44.5	39.0	41.3	41.9	44.2	22.2	23.0	23.2	20.8	27.0	27.0	21.4
	9	44.4	39.0	41.2	41.7	43.8	42.3	23.0	23.2	20.8	27.0	27.0	21.5
	1	44.4	39.0	41.2	41.7	43.7	41.9	38.7	23.2	20.8	27.1	27.1	21.5
	2	44.4	39.0	41.2	41.7	43.6	41.7	38.4	42.2	20.8	27.0	27.1	21.5
	3	44.4	38.9	41.2	41.6	43.5	41.7	38.3	41.9	37.6	27.0	27.1	21.6
	10	44.4	38.9	41.1	41.6	43.4	41.5	38.2	41.7	37.1	41.3	27.0	21.5
	11	44.3	38.9	41.1	41.6	43.4	41.5	38.2	41.7	37.1	41.1	40.8	21.6
	12	44.4	38.9	41.1	41.6	43.4	41.5	38.2	41.7	37.0	41.0	40.5	41.1
Touch-up Order	4	44.6	38.8	40.9	41.4	43.2	41.3	37.8	41.3	36.7	40.6	40.0	40.3
	5	44.5	42.1	40.9	41.4	43.1	41.2	37.8	41.3	36.7	40.6	40.0	40.3
	6	44.5	42.0	41.6	41.3	43.2	41.3	37.8	41.3	36.7	40.6	40.0	40.3
	7	44.5	42.0	41.5	42.9	43.2	41.2	37.8	41.3	36.7	40.6	40.0	40.3
	8	44.5	41.9	41.5	42.9	44.0	41.2	37.8	41.3	36.7	40.6	40.0	40.3
	9	44.5	42.0	41.5	42.9	44.0	42.8	37.9	41.3	36.7	40.6	40.0	40.3
	1	44.5	41.9	41.5	42.8	44.0	42.7	41.8	41.3	36.7	40.6	40.0	40.3
	2	44.5	41.9	41.4	42.8	43.9	42.7	41.6	43.7	36.7	40.5	39.9	40.2
	3	44.5	41.9	41.4	42.8	43.9	42.6	41.5	43.6	39.7	40.6	40.0	40.2
	10	44.4	41.8	41.4	42.7	43.8	42.6	41.3	43.4	39.4	42.5	39.9	40.2
	11	44.5	41.8	41.4	42.7	43.8	42.6	41.3	43.5	39.5	42.4	43.3	40.2
	12	44.4	41.8	41.4	42.7	43.8	42.6	41.3	43.4	39.4	42.4	43.2	41.5

Tension in Kips

Average Fastener Tension
(after snugging) = 22.6 Kips
(after tightening) = 40.9 Kips
(after touch-up) = 42.3 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates (3mm gap)
Cal. Wrench Installation (with 25 kip Snug)
Tightened from Middle to Outside

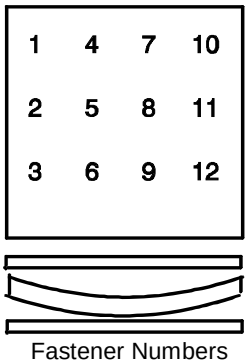


Figure B.46: Fastener Tensions for test CD3CW252.MTO

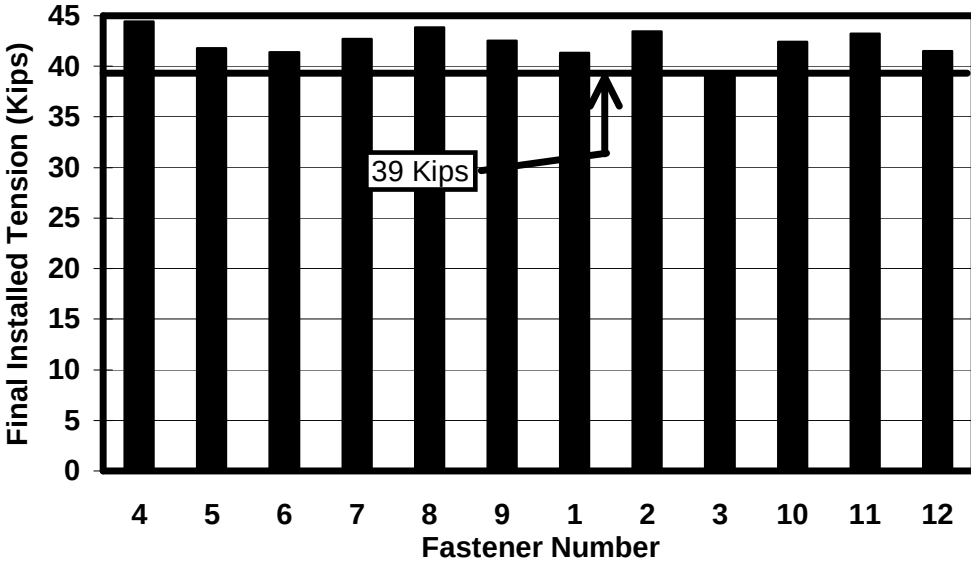


Figure B.47: Final Installed Tensions for Test CD3CW252.MTO

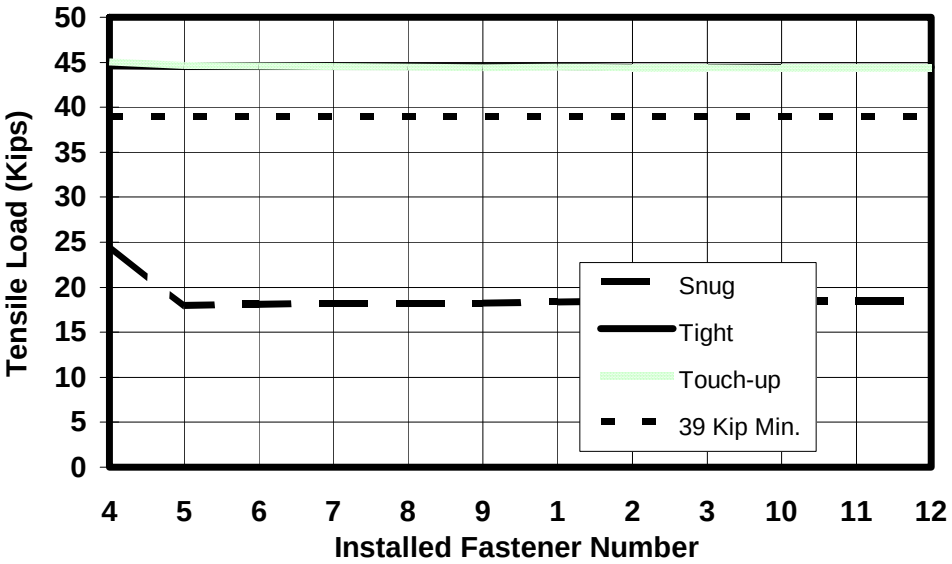


Figure B.48: Tensile Load History for Fastener #4 - Test CD3CW252.MTO

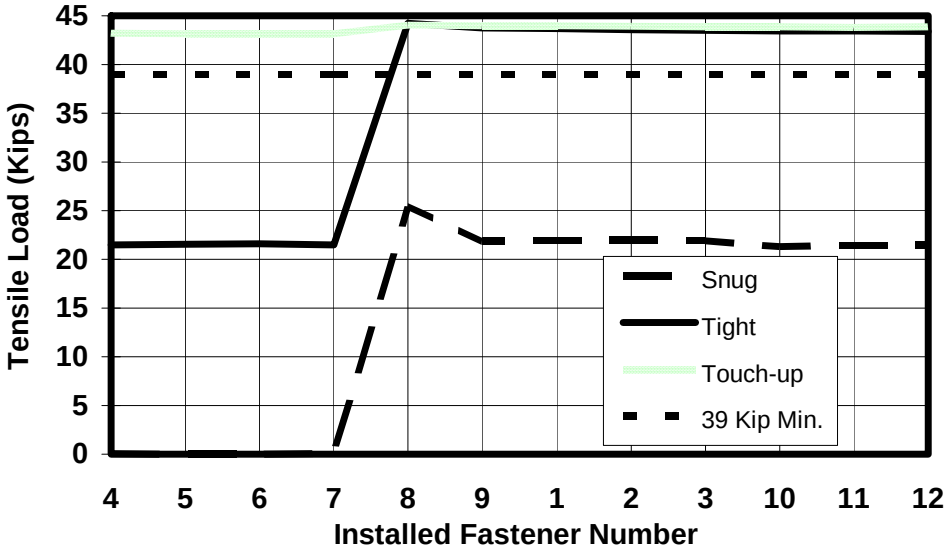


Figure B.49: **Tensile Load History for Fastener #8 - Test CD3CW252.MTO**

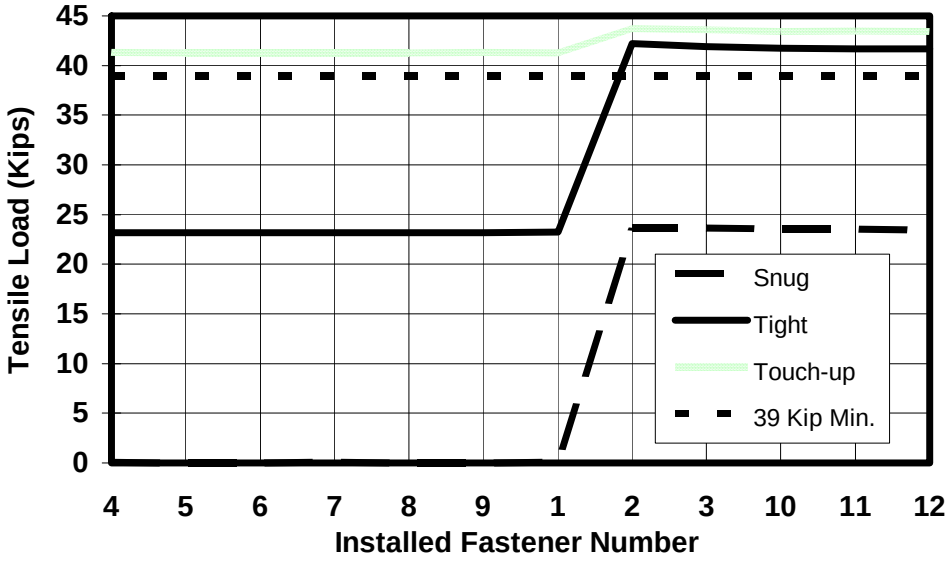


Figure B.50: **Tensile Load History for Fastener #2 - Test CD3CW252.MTO**

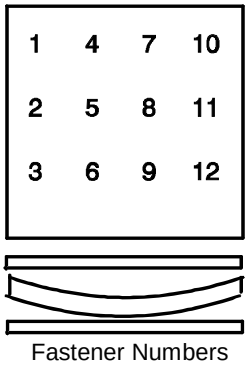
Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	23.3	0.2	0.2	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.4	0.3
	5	10.5	24.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3
	6	10.8	11.1	26.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3
	7	10.4	9.9	24.4	24.1	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.3
	8	12.1	9.9	23.1	15.1	29.0	0.2	0.2	0.3	0.2	0.2	0.2	0.4
	9	12.5	11.7	20.3	14.7	21.5	23.2	0.1	0.3	0.1	0.2	0.2	0.3
	1	4.8	5.9	17.0	15.9	22.1	23.7	25.0	0.2	0.2	0.2	0.2	0.4
	2	5.6	4.9	13.6	15.9	22.4	24.4	23.5	26.6	0.2	0.2	0.2	0.4
	3	5.7	5.7	11.4	15.9	22.5	25.1	23.6	23.8	26.7	0.3	0.3	0.4
	10	7.0	6.3	12.3	9.3	16.4	21.4	23.5	23.7	26.3	27.2	0.3	0.5
	11	7.0	6.5	12.8	9.9	15.2	18.2	23.4	23.7	26.1	26.5	28.7	0.5
	12	7.0	6.6	13.2	9.9	15.9	16.0	23.4	23.7	26.1	26.4	28.1	30.0
Tightening Order	4	41.5	6.0	12.9	20.4	15.2	16.3	23.0	23.5	BG	25.9	27.5	28.4
	5	41.0	39.9	12.3	22.6	13.5	16.0	23.2	23.5	BG	25.9	27.6	28.5
	6	41.0	39.2	37.4	23.5	13.5	13.5	23.2	23.6	BG	25.9	27.7	28.4
	7	40.2	39.1	36.9	45.7	13.6	13.6	23.2	23.6	BG	25.8	27.8	28.4
	8	40.2	38.8	36.7	47.1	40.6	13.6	23.2	23.6	BG	25.9	27.8	28.5
	9	40.2	38.8	34.5	46.9	40.3	41.8	23.1	23.6	BG	25.9	27.8	28.6
	1	40.2	38.8	34.5	49.2	40.2	41.6	39.3	23.8	BG	25.9	27.9	28.7
	2	40.2	38.7	34.6	47.5	40.2	41.5	39.2	41.8	BG	25.9	27.9	28.7
	3	40.2	38.8	34.5	47.5	40.1	41.4	39.0	41.4	BG	25.9	27.8	28.7
	10	40.2	38.8	34.5	48.0	40.1	41.4	39.0	41.3	BG	38.8	27.9	28.7
	11	40.1	38.7	34.5	47.4	40.1	41.4	38.9	41.2	BG	38.4	43.3	28.7
	12	40.1	38.7	34.5	47.4	40.1	41.4	38.9	41.1	BG	38.2	43.0	46.9
Touch-up Order	4	39.9	38.3	34.1	39.3	39.6	40.7	38.2	40.3	BG	37.1	42.2	44.5
	5	39.8	38.5	34.1	38.8	39.6	40.7	38.2	40.3	BG	37.1	42.2	44.6
	6	39.8	38.4	37.4	35.7	39.6	40.6	38.2	40.3	BG	37.1	42.2	44.5
	7	39.8	38.4	37.1	38.0	39.6	40.6	38.2	40.3	BG	37.1	42.2	44.6
	8	39.8	38.4	37.1	35.3	41.5	40.7	38.2	40.3	BG	37.1	42.2	44.6
	9	39.9	38.4	37.1	36.8	41.5	41.5	38.2	40.3	BG	37.1	42.2	44.6
	1	39.8	38.4	37.1	38.4	41.5	41.4	39.4	40.3	BG	37.2	42.3	44.6
	2	39.8	38.4	37.1	37.5	41.4	41.4	39.4	40.7	BG	37.1	42.2	44.6
	3	39.8	38.4	37.1	35.5	41.4	41.4	39.3	40.6	BG	37.1	42.2	44.6
	10	39.8	38.4	37.1	33.6	41.4	41.4	39.3	40.6	BG	37.8	42.2	44.6
	11	39.8	38.4	37.1	32.2	41.4	41.4	39.3	40.6	BG	37.8	42.4	44.6
	12	39.8	38.4	37.0	38.4	41.4	41.4	39.3	40.6	BG	37.8	42.4	45.4

Tension in Kips

Average Fastener Tension
(after snugging) = 18.9 Kips
(after tightening) = 41.0 Kips
(after touch-up) = 40.2 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates (3mm gap)
Cal. Wrench Installation (with 25 kip Snug)
Tightened from Middle to Outside



Fastener Numbers

Figure B.51: Fastener Tensions for test CD3CW253.MTO

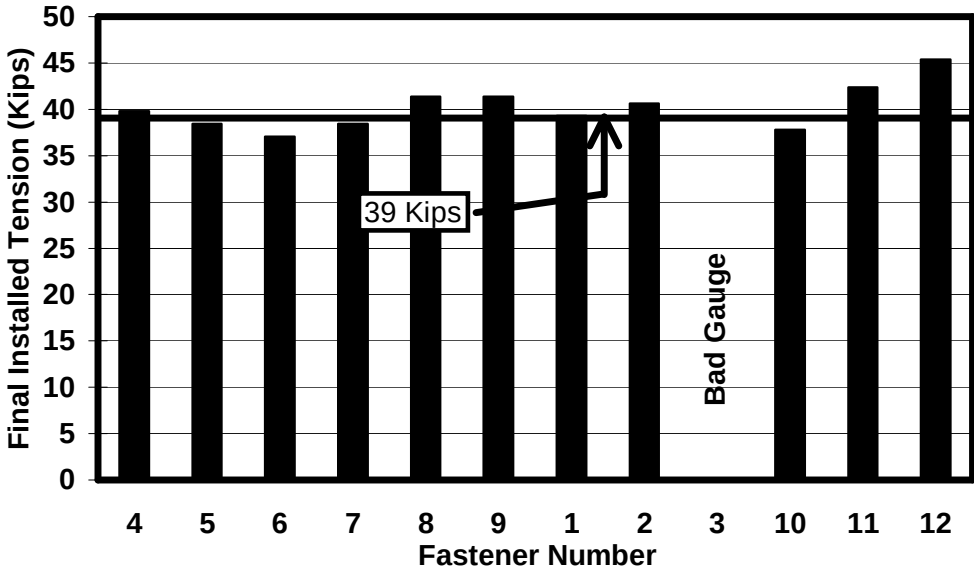


Figure B.52: **Final Installed Tensions for Test CD3CW253.MTO**

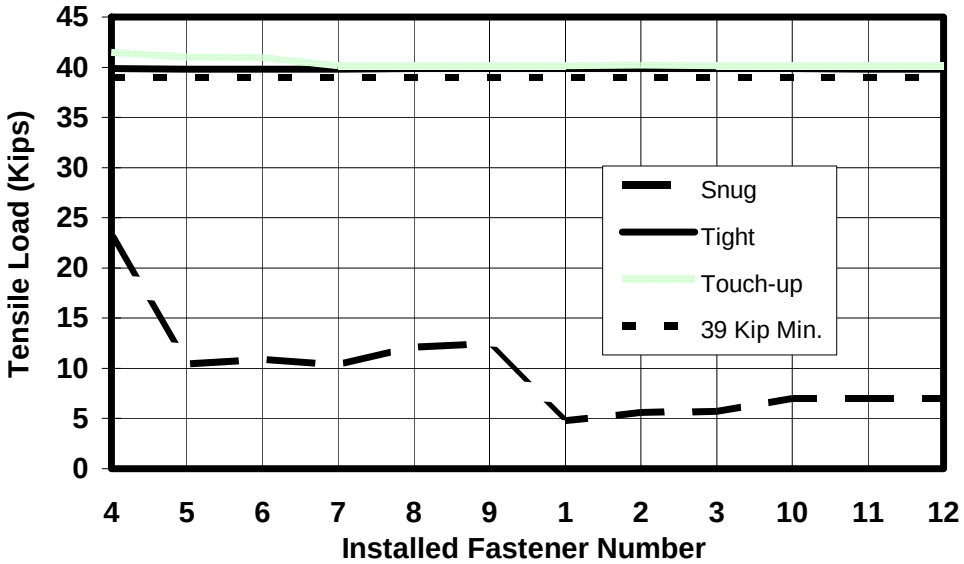


Figure B.53: **Tensile Load History for Fastener #4 - Test CD3CW253.MTO**

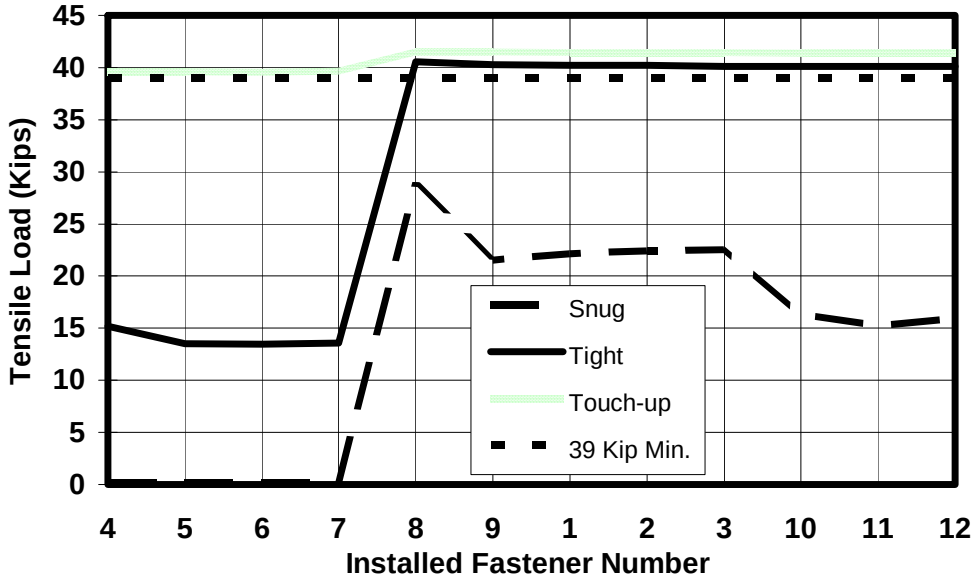


Figure B.54: **Tensile Load History for Fastener #8 - Test CD3CW253.MTO**

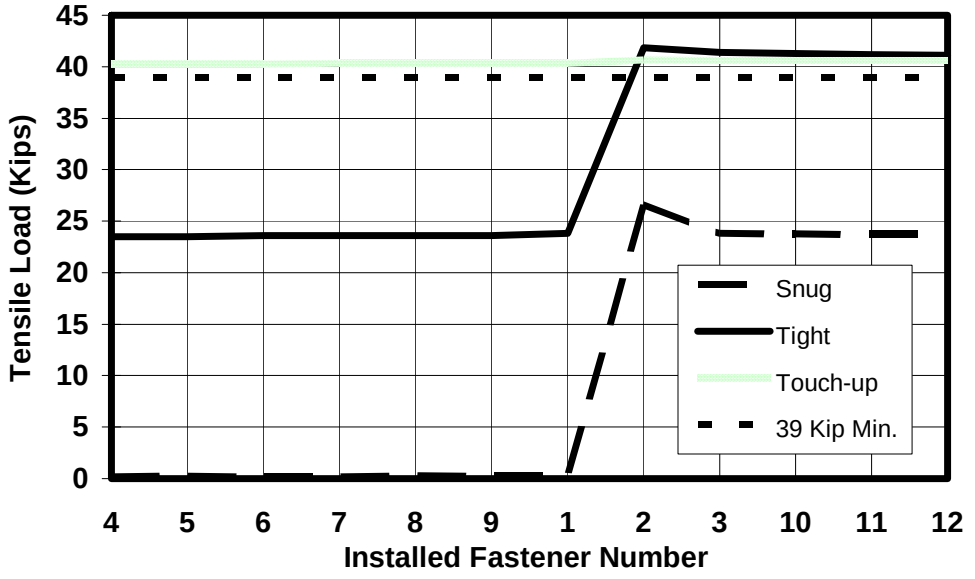


Figure B.55: **Tensile Load History for Fastener #2 - Test CD3CW253.MTO**

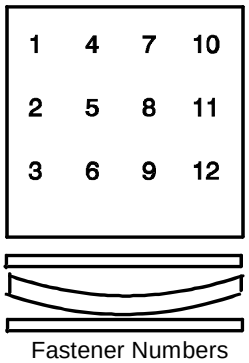
Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	25.9	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.9	0.4	2.6
	5	10.1	24.2	0.3	0.3	0.2	0.3	0.2	0.2	0.2	1.9	0.6	1.9
	6	10.1	7.5	22.8	0.2	0.2	0.3	0.2	0.2	0.2	2.4	0.6	1.4
	7	2.4	5.4	22.7	26.8	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.3
	8	3.4	4.5	18.7	11.4	27.7	0.4	0.2	0.3	0.3	0.4	0.3	0.3
	9	4.9	5.8	13.6	10.2	15.9	23.7	0.2	0.2	0.2	0.3	0.3	0.2
	1	0.3	0.3	5.5	16.0	20.3	28.7	23.3	0.3	0.3	0.4	0.4	0.3
	2	0.3	0.1	0.7	17.6	22.0	31.2	8.9	24.5	0.3	0.4	0.4	0.3
	3	0.2	0.0	0.2	18.1	23.2	30.8	9.0	10.0	26.2	0.3	0.3	0.3
	10	0.2	0.7	0.3	4.7	13.1	24.9	10.3	9.8	26.0	23.9	0.3	0.3
	11	0.2	0.8	0.3	5.8	8.1	18.6	10.1	9.6	26.4	13.0	26.2	0.3
	12	0.2	0.7	0.3	6.3	8.0	12.4	9.9	9.5	26.3	14.6	18.2	25.2
Tightening Order	4	42.6	0.2	0.6	1.1	4.4	13.0	7.5	9.4	26.4	14.6	18.5	24.8
	5	39.1	40.3	0.5	0.8	2.4	10.0	8.1	9.5	25.9	14.7	18.4	24.8
	6	39.2	37.7	41.1	0.9	2.1	5.2	8.2	10.3	24.6	14.8	18.5	24.2
	7	35.7	36.9	40.7	49.6	1.4	5.2	8.4	10.5	24.7	12.8	18.7	24.3
	8	35.6	35.4	39.8	47.9	48.0	4.4	8.4	10.5	24.8	13.3	18.5	24.4
	9	35.7	35.3	35.8	47.8	46.6	44.0	8.4	10.7	25.0	13.4	18.8	23.8
	1	35.7	35.5	35.9	47.8	46.5	43.5	40.5	8.9	24.8	13.4	18.9	23.8
	2	35.9	35.6	36.1	47.8	46.5	43.5	40.2	40.3	23.9	13.4	18.9	23.8
	3	35.9	35.7	35.9	47.8	46.5	43.4	40.1	39.7	40.1	13.5	18.9	23.9
	10	35.9	35.7	36.0	47.5	46.6	43.4	40.1	39.7	39.9	41.8	18.9	23.9
	11	35.9	35.7	36.0	47.5	46.5	43.5	40.1	39.6	39.9	41.5	41.8	23.6
	12	35.9	35.7	36.0	47.6	46.5	43.3	40.1	39.6	39.8	41.4	41.4	42.5
Touch-up Order	4	38.9	34.3	34.8	45.7	44.9	41.4	38.7	37.8	38.2	39.3	39.5	40.2
	5	38.9	37.8	34.9	45.8	45.0	41.5	38.8	37.9	38.3	39.4	39.6	40.4
	6	38.9	37.7	39.0	45.8	45.0	41.2	38.8	37.9	38.3	39.4	39.6	40.3
	7	38.8	37.6	38.9	49.4	44.9	41.1	38.8	37.8	38.2	39.3	39.6	40.3
	8	38.9	37.8	39.1	49.5	46.0	41.4	38.9	38.0	38.4	39.6	39.8	40.5
	9	38.9	37.7	38.9	49.4	45.9	42.8	38.9	37.9	38.3	39.5	39.7	40.4
	1	38.7	37.6	38.8	49.2	45.8	42.6	40.2	37.8	38.2	39.3	39.5	40.3
	2	38.8	37.6	38.8	49.2	45.8	42.6	40.1	40.4	38.2	39.4	39.6	40.3
	3	38.6	37.4	38.6	49.0	45.6	42.4	39.9	40.1	39.3	39.1	39.4	40.1
	10	38.6	37.4	38.6	49.0	45.6	42.3	39.9	40.1	39.2	42.0	39.3	40.1
	11	38.7	37.6	38.8	49.2	45.8	42.6	40.1	40.3	39.3	42.2	40.8	40.3
	12	38.6	37.5	38.6	49.0	45.6	42.4	39.9	40.1	39.2	41.9	40.6	41.9

Tension in Kips

Average Fastener Tension
(after snugging) = 11.0 Kips
(after tightening) = 40.8 Kips
(after touch-up) = 41.3 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates (3mm gap)
Cal. Wrench Installation (with 25 kip Snug)
Tightened from Middle to Outside



Fastener Numbers

Figure B.56: Fastener Tensions for test CD3CW254.MTO

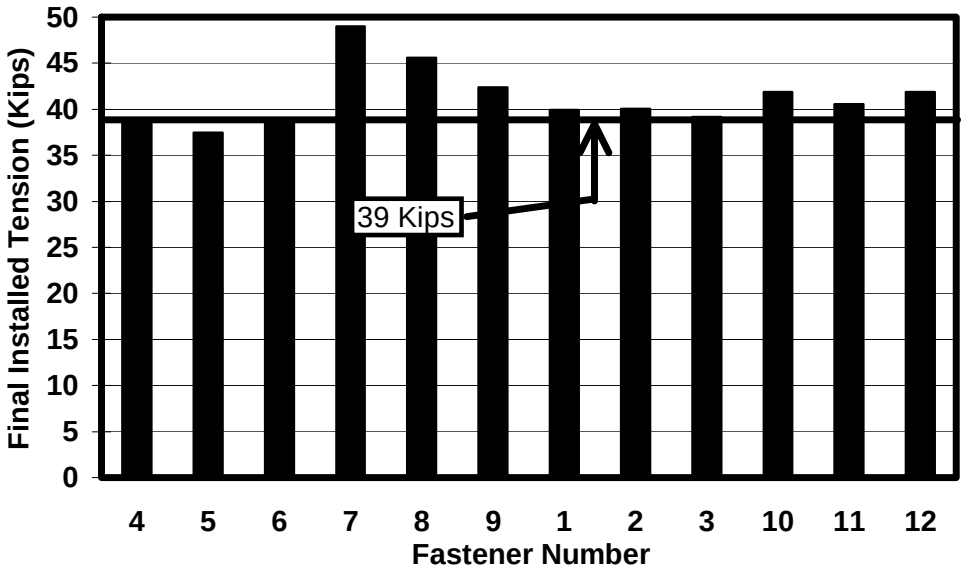


Figure B.57: **Final Installed Tensions for Test CD3CW254.MTO**

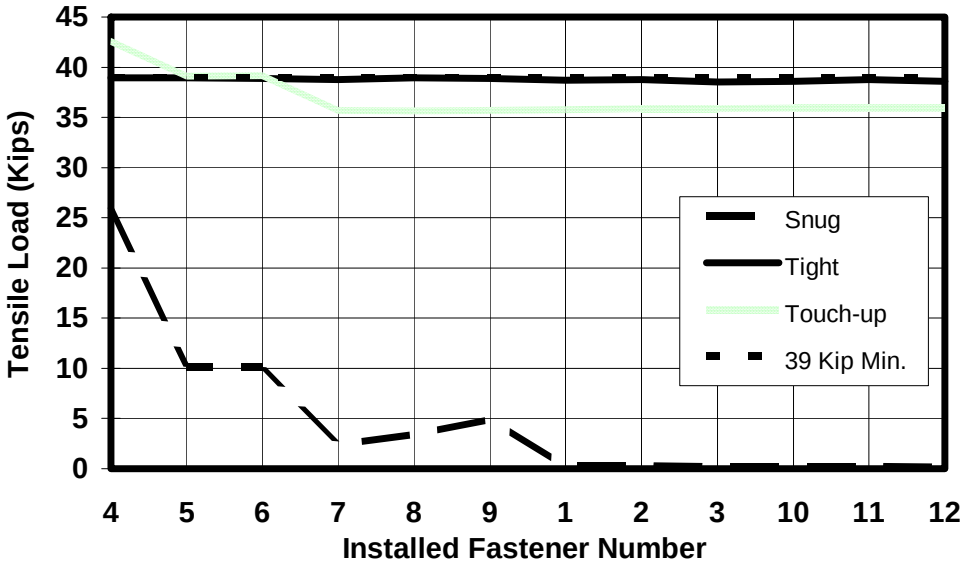


Figure B.58: **Tensile Load History for Fastener #4 - Test CD3CW254.MTO**

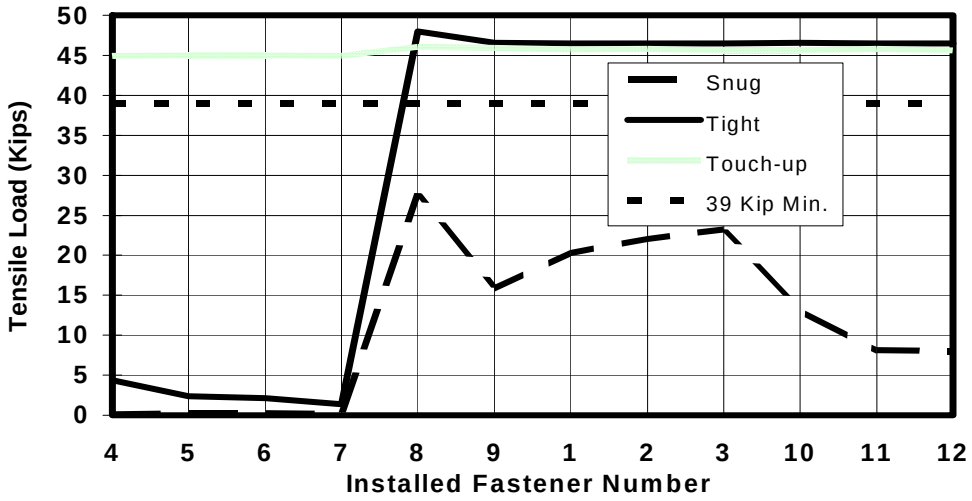


Figure B.59: **Tensile Load History for Fastener #8 - Test CD3CW254.MTO**

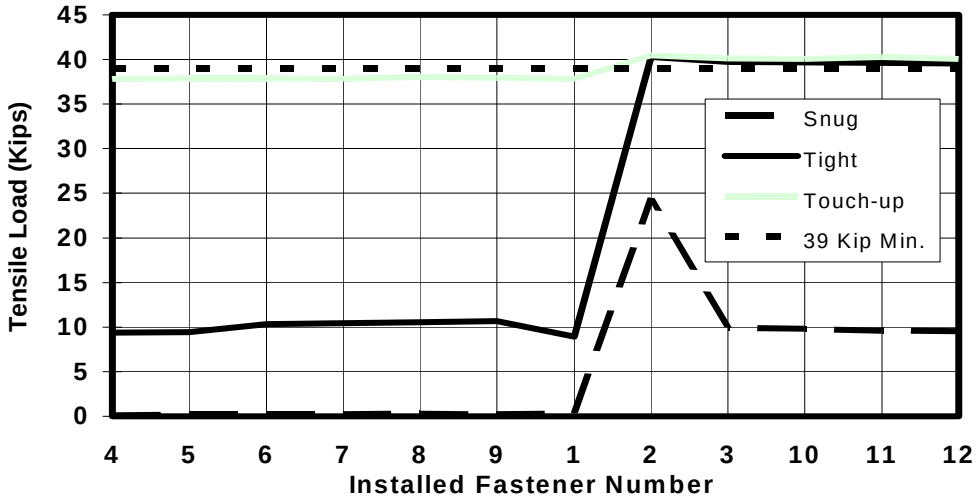


Figure B.60: **Tensile Load History for Fastener #2 - Test CD3CW254.MTO**

		Fastener Number											
		1	2	3	4	5	6	7	8	9	10	11	12
Snugging Order	1	11.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.5
	2	6.0	12.1	0.0	0.0	-0.1	0.0	0.0	-0.1	0.0	0.0	0.4	0.5
	3	5.8	7.8	12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3
	4	6.3	7.3	11.4	13.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.5
	5	6.4	7.9	10.0	9.0	12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
	6	6.5	8.2	9.5	9.3	7.8	13.5	0.1	0.1	0.0	0.0	0.0	0.0
	7	6.4	8.3	9.4	6.8	6.5	12.5	8.9	0.0	0.0	0.0	0.0	0.0
	8	6.3	8.2	9.4	6.5	4.2	10.2	5.2	13.8	-0.1	-0.1	-0.1	0.0
	9	6.3	8.3	9.7	6.8	4.2	6.0	5.4	8.6	14.4	-0.1	0.0	0.0
	10	6.4	8.4	9.7	7.6	4.7	6.4	4.5	7.3	13.3	13.6	0.0	0.0
	11	6.4	8.3	9.7	7.5	4.8	6.6	4.6	7.5	12.7	13.5	14.2	0.0
	12	6.4	8.3	9.7	7.5	4.8	6.7	4.6	7.6	12.5	13.3	14.1	11.6
Tightening Order	1	41.2	8.1	9.2	7.5	4.5	6.4	4.3	7.3	12.5	12.5	13.3	10.6
	2	40.8	43.6	9.5	7.6	4.8	6.5	4.3	7.3	12.5	12.5	13.3	10.6
	3	40.5	42.8	39.0	7.6	4.9	6.9	4.4	7.4	12.6	12.6	13.3	10.6
	4	40.6	42.8	38.5	42.2	4.0	6.9	2.8	6.7	12.7	12.6	13.3	10.6
	5	40.6	42.9	38.5	41.8	39.8	6.5	2.9	5.5	12.5	12.7	13.4	10.7
	6	40.6	42.9	38.4	41.7	39.5	40.9	2.9	5.6	11.6	12.6	13.4	10.7
	7	40.5	42.9	38.3	41.4	39.3	40.6	34.5	5.0	11.6	13.0	13.4	10.6
	8	40.5	42.8	38.2	41.4	39.2	40.4	33.8	42.0	11.3	12.9	13.7	10.6
	9	40.4	42.8	38.2	41.3	39.2	40.4	33.7	41.5	43.0	12.9	13.7	10.9
	10	40.4	42.7	38.1	41.3	39.1	40.3	33.6	41.3	42.5	41.2	13.8	10.9
	11	40.5	42.8	38.1	41.3	39.1	40.3	33.6	41.3	42.3	40.8	38.8	11.2
	12	40.4	42.7	38.0	41.2	39.1	40.2	33.5	41.2	42.2	40.6	38.4	41.5
Touch-up Order	1	40.3	42.4	37.8	40.9	38.7	39.9	33.1	40.7	41.6	39.9	37.7	40.3
	2	40.2	43.7	37.8	40.9	38.7	39.9	33.1	40.7	41.6	39.9	37.7	40.3
	3	40.2	43.6	39.9	43.6	41.2	39.9	33.1	40.7	41.6	39.9	37.7	40.2
	4	40.2	43.6	39.8	43.5	41.1	43.0	33.1	40.7	41.6	39.9	37.7	40.2
	5	40.1	43.5	39.8	43.5	41.1	42.9	33.1	40.7	41.6	39.9	37.7	40.2
	6	40.2	43.5	39.8	43.4	41.0	42.9	33.1	40.7	41.6	39.9	37.7	40.2
	7	40.2	43.5	39.7	43.4	41.0	42.9	34.5	40.7	41.6	39.9	37.7	40.2
	8	40.1	43.5	39.7	43.4	41.0	42.9	34.4	42.7	44.8	39.9	37.7	40.2
	9	40.2	43.5	39.7	43.4	41.0	42.9	34.4	42.7	44.7	39.9	37.7	40.2
	10	40.1	43.5	39.7	43.4	40.9	42.8	34.3	42.6	44.6	42.6	37.7	40.2
	11	40.2	43.5	39.7	43.4	40.9	42.8	34.3	42.6	44.6	42.5	41.5	43.3
	12	40.2	43.5	39.7	43.4	40.9	42.8	34.3	42.6	44.6	42.4	41.4	43.2

Tension in Kips

Average Fastener Tension
(after snugging) = 8.9 Kips
(after tightening) = 39.9 Kips
(after touch-up) = 41.6 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates (3mm gap)
Cal. Wrench Installation (with 12 kip Snug)
Tightened from Top Left to Bottom Right

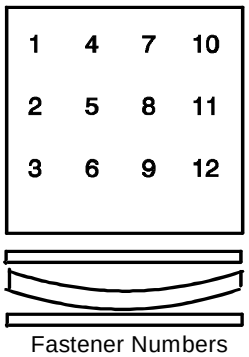


Figure B.61: Fastener Tensions for test CD3CW122.LTR

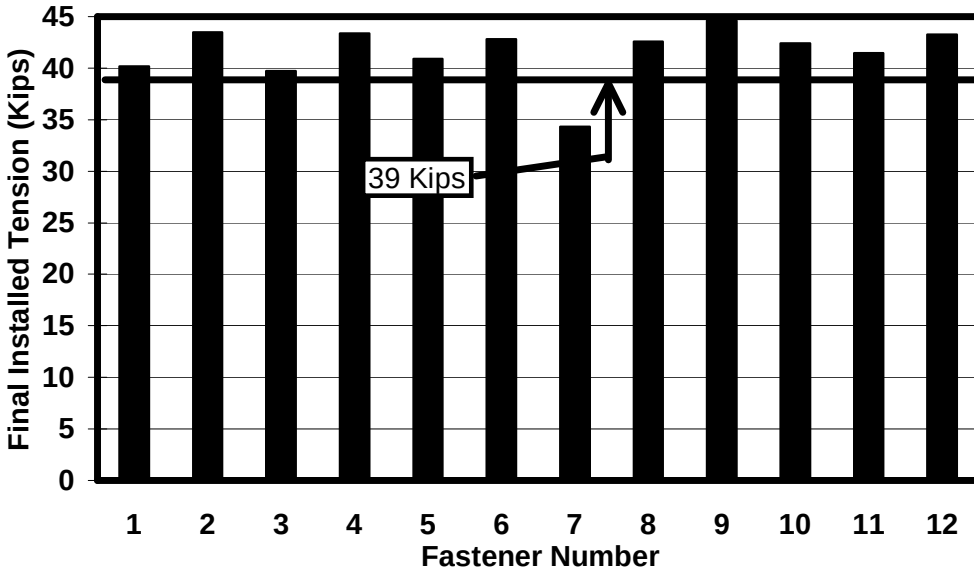


Figure B.62: **Final Installed Tensions for Test CD3CW122.LTR**

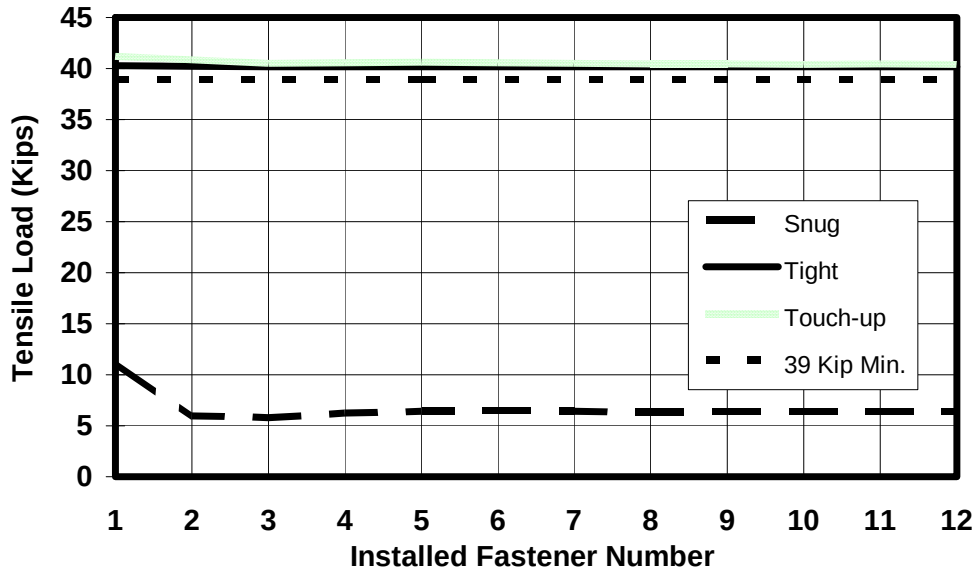


Figure B.63: **Tensile Load History for Fastener #1 - Test CD3CW122.LTR**

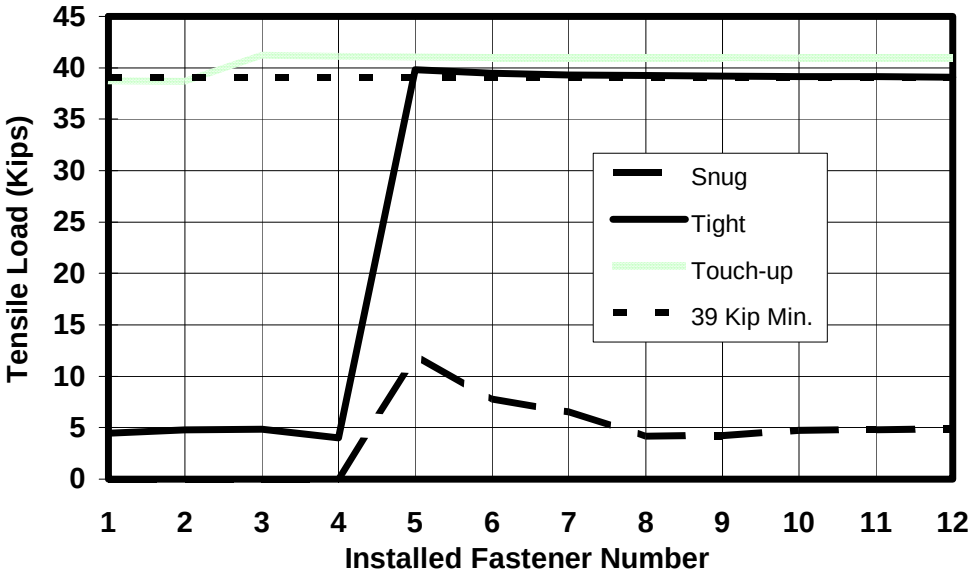


Figure B.64: **Tensile Load History for Fastener #5 - Test CD3CW122.LTR**

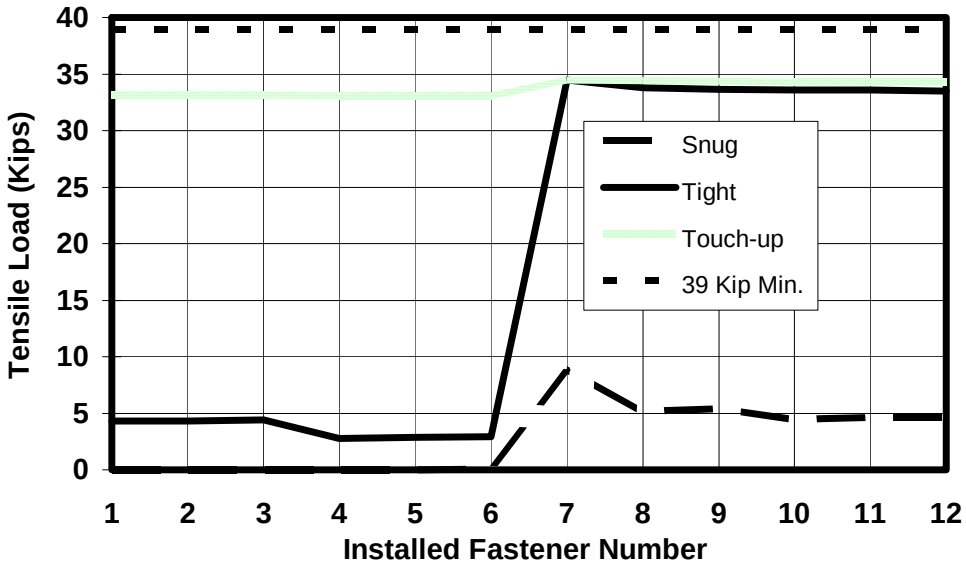


Figure B.65: **Tensile Load History for Fastener #7 - Test CD3CW122.LTR**

Fastener Number

		1	2	3	4	5	6	7	8	9	10	11	12
Snugging	1	12.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	1.2	2.5	0.0
	2	7.2	10.6	0.0	0.0	0.0	0.0	0.0	0.1	0.0	1.4	3.2	0.2
	3	7.4	4.2	10.3	0.0	0.0	0.0	0.0	0.0	0.0	1.4	3.7	0.1
	4	3.4	2.6	8.6	8.5	0.0	0.1	0.1	0.1	0.1	0.6	3.7	0.2
	5	3.3	1.5	7.6	2.8	9.9	0.0	0.0	0.0	0.0	0.6	2.8	0.0
	6	3.5	1.5	5.9	2.9	3.4	11.3	0.0	0.0	0.0	0.7	2.0	0.0
	7	3.5	1.6	6.6	-0.1	0.7	9.4	12.1	-0.1	0.0	0.0	0.0	0.0
	8	3.8	1.5	7.8	-0.1	0.0	4.9	5.5	10.7	0.0	0.0	-0.1	0.0
	9	4.1	1.9	9.0	0.1	0.1	1.0	6.6	2.4	12.4	0.1	0.1	0.2
	10	5.4	2.0	9.9	0.6	1.0	3.2	0.2	0.2	8.4	13.3	0.2	0.2
	11	5.3	1.8	10.5	0.8	1.0	4.1	0.0	0.0	3.5	5.5	11.9	0.1
	12	5.2	2.1	11.8	1.3	1.5	3.9	0.2	0.2	0.7	6.7	3.5	12.1
Tightening	1	41.6	1.1	12.1	0.5	0.7	4.0	0.5	0.5	1.0	6.6	3.8	12.0
	2	41.1	43.8	8.1	0.5	0.4	2.7	0.5	0.5	0.9	6.4	3.7	11.9
	3	41.1	44.0	41.9	0.5	0.4	0.9	0.6	0.5	0.6	6.5	3.8	12.0
	4	40.5	43.8	41.3	40.8	0.4	0.6	0.6	0.6	0.6	5.4	3.6	12.0
	5	40.8	44.0	40.1	36.1	43.3	0.6	0.6	0.6	0.6	5.7	3.4	11.1
	6	40.7	44.2	40.2	36.0	39.6	44.4	0.5	0.5	0.6	6.0	3.7	9.7
	7	40.8	44.2	40.3	34.5	39.3	44.1	44.1	0.6	0.7	1.2	2.4	10.0
	8	40.8	44.2	40.2	34.7	38.4	43.0	43.1	41.1	0.7	1.0	1.0	7.9
	9	40.8	44.2	40.4	34.7	38.7	39.4	43.1	39.5	42.9	1.4	0.9	3.4
	10	40.8	44.2	40.4	34.7	38.7	39.5	42.5	39.1	42.6	46.6	0.6	2.5
	11	40.9	44.2	40.3	34.7	38.7	39.5	42.6	38.9	42.0	46.3	47.5	0.9
	12	40.9	44.2	40.3	34.7	38.7	39.6	42.6	39.2	40.9	46.2	47.0	46.3
Tightening Order	1	41.8	44.2	40.4	34.8	38.7	39.6	42.6	39.1	41.0	46.2	46.8	45.6
	2	41.8	45.1	40.4	34.8	38.7	39.6	42.6	39.1	41.0	46.2	46.7	45.6
	3	41.8	45.1	41.7	34.8	38.8	39.7	42.6	39.2	41.0	46.2	46.8	45.6
	4	41.8	45.1	41.7	36.7	38.8	39.7	42.6	39.2	41.0	46.2	46.8	45.6
	5	41.8	45.1	41.7	36.7	42.6	39.7	42.6	39.2	41.1	46.2	46.8	45.7
	6	41.8	45.1	41.7	36.7	42.5	42.8	42.6	39.2	41.0	46.2	46.8	45.7
	7	41.8	45.1	41.7	36.6	42.5	42.8	43.9	39.2	41.0	46.3	46.8	45.7
	8	41.8	45.0	41.7	36.6	42.5	42.7	43.8	40.1	41.0	46.2	46.8	45.6
	9	41.8	45.0	41.7	36.6	42.4	42.6	43.8	40.1	41.8	46.2	46.8	45.6
	10	41.8	45.0	41.7	36.6	42.4	42.6	43.8	40.1	41.7	47.4	46.8	45.6
	11	41.8	45.1	41.6	36.6	42.4	42.6	43.8	40.1	41.7	47.4	48.4	45.6
	12	41.8	45.1	41.7	36.6	42.5	42.7	43.8	40.1	41.8	47.4	48.3	46.5

Tension in Kips

Average Fastener Tension
(after snugging) = 4.1 Kips
(after tightening) = 41.7 Kips
(after 2nd tightening)= 43.2 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates (3mm gap)
Cal. Wrench Installation (with 12 kip Snug)
Tightened from Top Left to Bottom Right

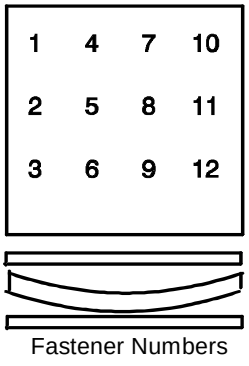


Figure B.66: Fastener Tensions for test CD3CW123.LTR

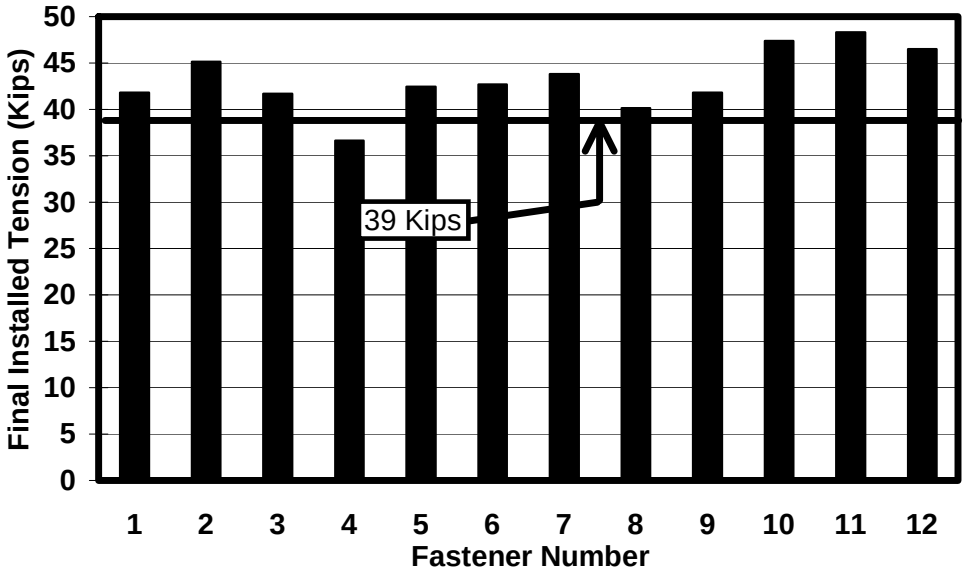


Figure B.67: **Final Installed Tensions for Test CD3CW123.LTR**

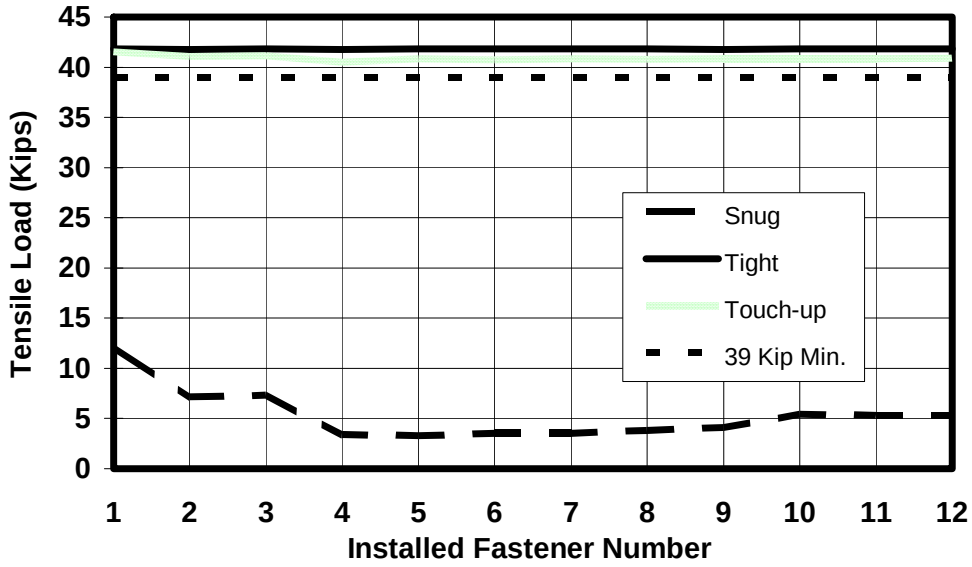


Figure B.68: **Tensile Load History for Fastener #1 - Test CD3CW123.LTR**

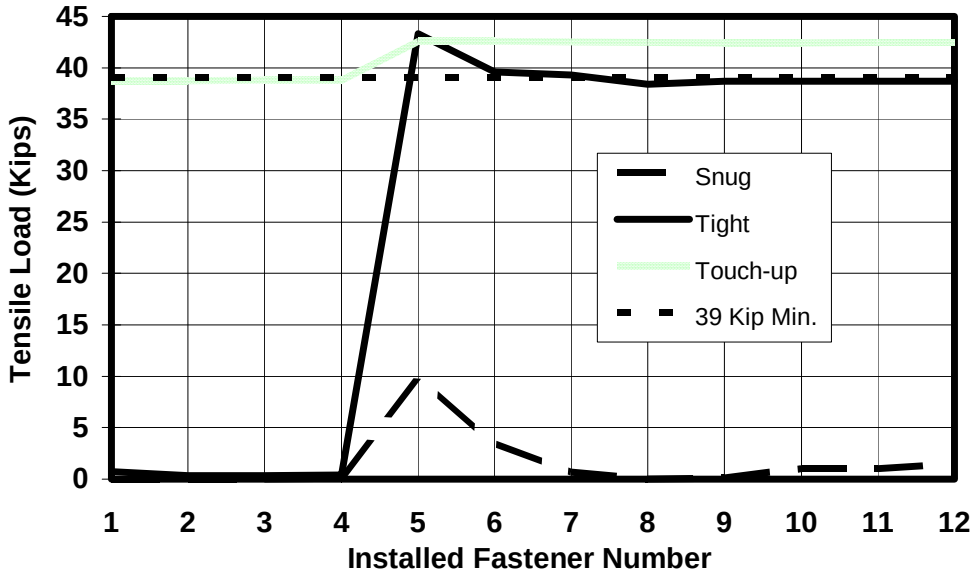


Figure B.69: **Tensile Load History for Fastener #5 - Test CD3CW123.LTR**

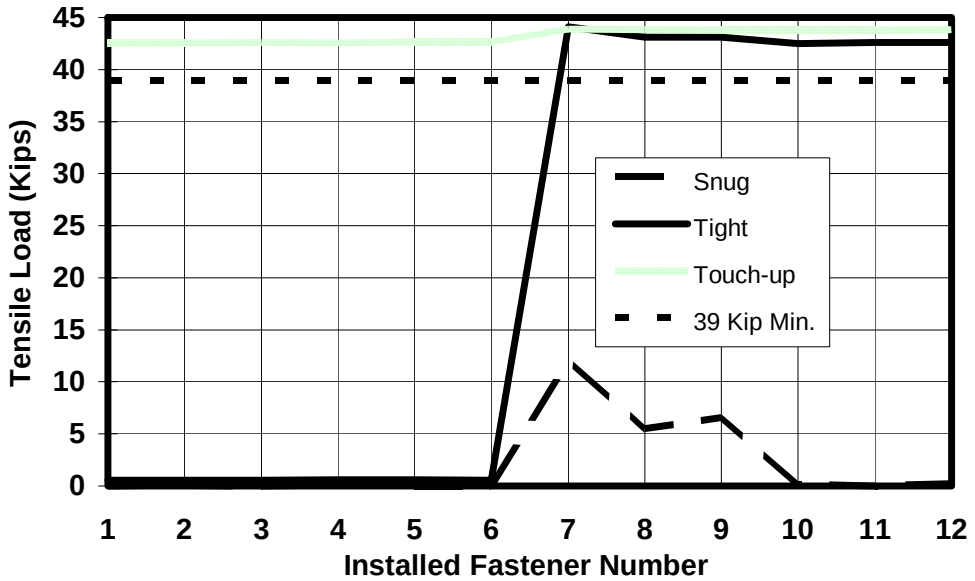


Figure B.70: **Tensile Load History for Fastener #7 - Test CD3CW123.LTR**

		Fastener Number											
		1	2	3	4	5	6	7	8	9	10	11	12
Snugging Order	1	11.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	5.7	0.4
	2	5.2	12.9	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	6.8	0.4
	3	5.4	6.9	11.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	7.3	0.2
	4	1.3	4.3	10.0	12.0	0.0	0.0	0.1	0.0	0.1	0.0	5.3	0.2
	5	1.5	2.8	7.3	6.3	11.6	0.1	0.1	0.1	0.1	0.1	4.5	0.1
	6	1.9	2.7	3.7	5.9	5.1	12.0	0.1	0.1	0.1	0.1	3.7	0.0
	7	2.6	3.5	4.4	1.2	2.2	10.9	12.3	0.1	0.1	0.1	0.9	0.1
	8	3.1	3.7	5.2	1.0	1.0	7.0	7.2	11.4	0.1	0.0	0.0	0.0
	9	3.9	4.8	6.2	1.3	0.9	2.4	6.6	4.1	11.8	1.2	0.0	0.0
	10	5.5	5.8	7.6	2.4	1.9	4.2	0.9	0.9	8.2	12.5	0.0	0.0
	11	5.7	6.1	8.9	2.7	2.2	5.3	1.0	0.1	3.3	4.5	12.1	0.0
	12	5.6	6.3	10.0	3.0	2.4	4.7	1.5	0.1	0.7	4.6	3.6	10.9
Tightening Order	1	41.6	0.5	7.6	0.3	0.5	4.6	0.5	0.0	0.8	5.1	3.7	10.6
	2	35.1	43.5	0.8	0.1	0.2	1.7	0.2	0.0	0.5	5.2	3.4	11.3
	3	34.9	36.2	39.7	0.1	0.1	0.4	0.2	0.1	0.2	5.6	3.5	10.3
	4	28.0	30.6	36.3	42.6	0.2	0.3	0.1	0.1	0.1	4.7	2.6	10.3
	5	28.6	29.5	32.7	35.3	39.3	0.2	0.0	0.0	0.1	5.1	2.0	9.2
	6	28.8	30.7	29.2	34.8	31.1	40.2	0.0	0.1	0.1	5.6	2.2	7.2
	7	29.2	30.9	29.3	29.0	28.3	39.0	39.8	0.0	0.1	0.1	0.4	6.8
	8	29.2	31.1	29.4	29.1	26.2	36.8	32.1	39.4	0.1	0.1	0.1	2.8
	9	29.3	31.2	29.8	29.4	26.3	30.1	31.4	30.6	42.1	0.1	0.1	0.0
	10	29.4	31.3	29.9	30.2	26.7	30.7	22.7	22.9	35.8	42.0	0.1	0.1
	11	29.3	31.2	29.8	30.2	26.9	31.0	23.4	20.3	29.9	39.6	45.6	0.0
	12	29.3	31.2	29.9	30.2	26.8	31.1	23.4	20.8	28.1	39.7	43.5	43.5
Touch-up Order	1	40.3	31.2	29.9	30.0	26.7	30.9	23.5	20.9	28.7	39.5	43.2	42.6
	2	40.2	40.6	29.8	30.1	26.7	31.0	23.5	20.9	28.7	39.6	43.2	42.6
	3	40.1	40.5	36.8	30.1	26.7	31.0	23.5	20.9	28.7	39.5	43.2	42.7
	4	40.1	40.5	36.7	41.9	26.7	31.0	22.8	20.8	28.7	39.5	43.2	42.6
	5	40.0	40.4	36.7	41.8	37.2	30.9	22.8	20.6	28.7	39.5	43.2	42.6
	6	40.0	40.5	36.7	41.7	37.0	38.9	22.8	20.6	28.1	39.5	43.2	42.6
	7	40.0	40.4	36.6	41.2	36.9	38.7	37.0	20.3	28.1	39.4	43.2	42.6
	8	40.0	40.4	36.7	41.1	36.5	38.7	36.6	39.7	27.9	39.5	43.1	42.6
	9	40.1	40.5	36.7	41.1	36.6	37.8	36.6	39.6	42.8	39.5	43.2	42.6
	10	40.1	40.5	36.7	41.2	36.5	37.9	36.6	39.6	42.6	41.0	43.2	42.6
	11	40.0	40.5	36.7	41.1	36.4	37.8	36.5	39.4	42.5	40.9	44.6	42.5
	12	40.1	40.5	36.7	41.1	36.6	37.9	36.5	39.5	42.5	40.9	44.6	43.9

Tension in Kips

Average Fastener Tension
(after snugging) = 4.5 Kips
(after tightening) = 31.4 Kips
(after touch-up) = 40.1 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates (3mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Top Left to Bottom Right

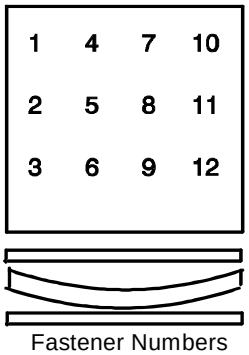


Figure B.71: Fastener Tensions for test CD3CW124.LTR

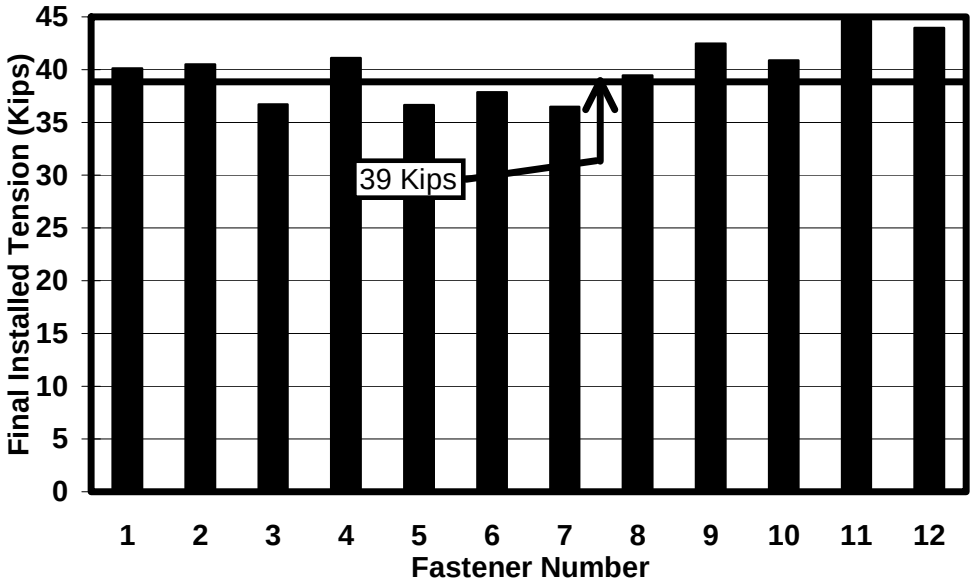


Figure B.72: **Tensile Load History for Fastener #1 - Test CD3CW124.LTR**

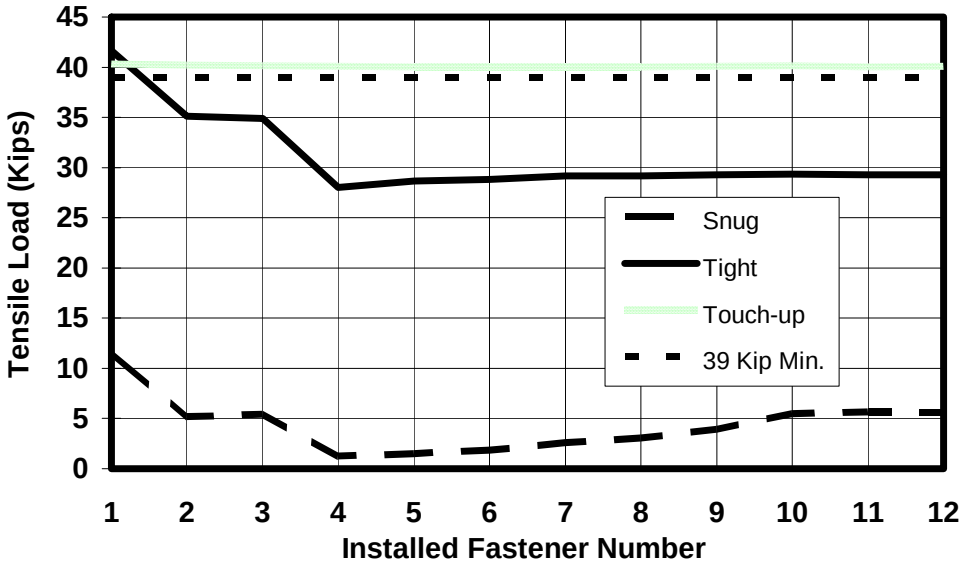


Figure B.73: **Tensile Load History for Fastener #1 - Test CD3CW124.LTR**

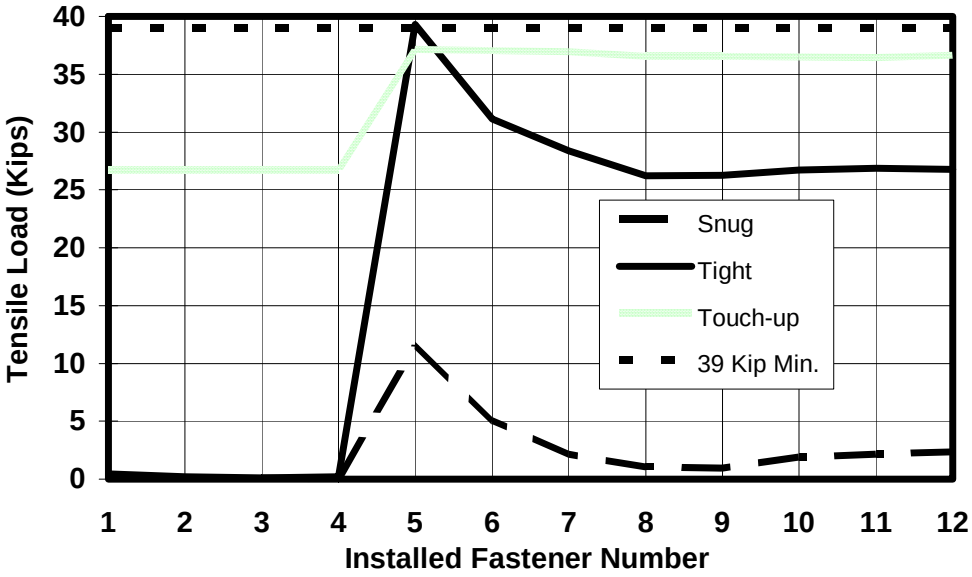


Figure B.74: **Tensile Load History for Fastener #5 - Test CD3CW124.LTR**

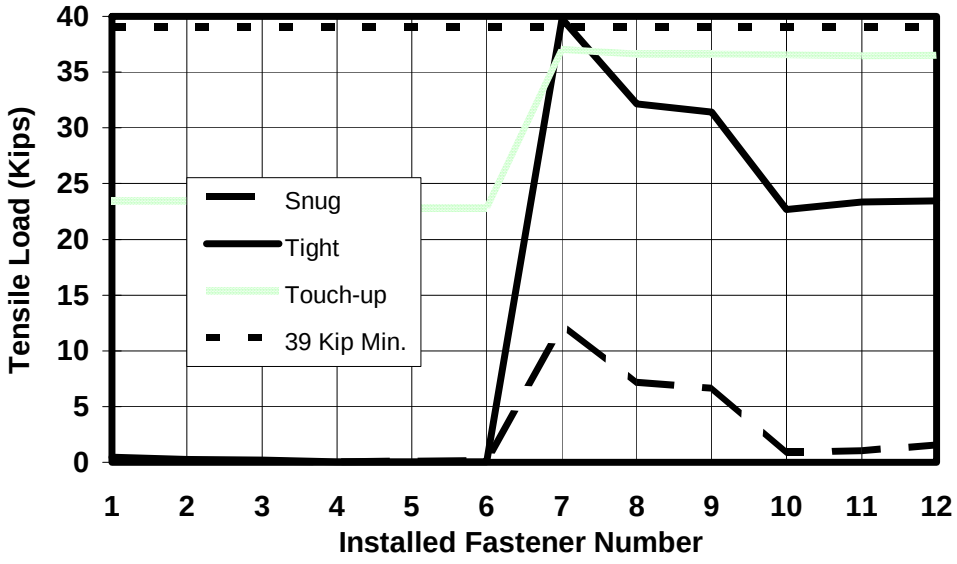


Figure B.75: **Tensile Load History for Fastener #7 - Test CD3CW124.LTR**

Fastener Number

		1	2	3	10	11	12	4	5	6	7	8	9
Snugging Order	1	10.7	0.0	0.0	0.4	0.0	0.1	0.0	0.0	0.7	0.0	0.0	0.0
	2	6.0	10.3	0.0	0.5	0.1	0.2	0.0	0.0	0.6	0.0	0.0	0.1
	3	5.7	5.9	11.5	0.5	0.1	0.1	0.0	0.0	0.7	0.0	0.0	0.1
	10	5.4	5.6	10.4	12.0	0.1	0.2	0.1	0.1	0.5	0.2	0.2	0.2
	11	5.3	5.3	9.3	9.6	12.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1
	12	5.4	5.3	8.1	9.5	10.9	12.9	0.1	0.0	0.4	0.1	0.1	0.1
	4	5.9	5.4	8.3	9.0	10.5	12.4	13.5	0.1	0.3	0.1	0.1	0.1
	5	6.1	6.1	7.8	9.2	10.4	11.9	10.6	11.9	0.2	0.1	0.1	0.1
	6	6.1	6.1	7.2	9.1	10.4	11.4	10.8	9.0	10.9	0.1	0.1	0.1
	7	6.1	6.1	7.3	9.4	10.6	11.4	8.2	8.4	11.4	9.3	0.1	0.1
	8	6.2	6.2	7.4	9.7	10.9	11.6	7.8	6.3	10.5	7.7	11.6	0.1
	9	6.1	6.2	7.5	9.6	10.9	12.1	7.9	6.0	7.3	7.8	9.5	12.4
Tightening Order	1	43.3	6.5	7.4	9.5	10.8	11.9	8.2	6.2	6.2	7.7	9.2	11.6
	2	42.8	40.0	7.8	9.5	10.8	11.9	8.3	6.5	6.2	7.7	9.3	11.6
	3	42.8	39.8	44.4	9.6	10.9	12.0	8.4	6.6	3.4	7.8	9.4	11.8
	10	42.7	39.5	43.9	40.8	11.0	11.9	8.3	6.6	3.1	7.9	9.3	11.7
	11	42.6	39.5	43.7	40.4	40.0	12.1	8.3	6.6	2.9	8.0	9.6	11.7
	12	42.6	39.4	43.7	40.4	39.7	40.0	8.4	6.6	2.8	8.0	9.7	12.1
	4	42.6	39.3	43.6	40.2	39.5	39.7	44.2	6.0	2.6	7.0	9.3	12.1
	5	42.5	39.4	43.5	40.1	39.3	39.5	43.9	44.8	2.3	7.0	8.2	11.9
	6	42.5	39.3	43.5	40.1	39.3	39.4	43.8	44.4	36.5	7.1	8.3	10.6
	7	42.5	39.3	43.4	40.1	39.3	39.3	43.6	44.2	36.3	39.7	7.8	10.6
	8	42.5	39.3	43.4	40.1	39.3	39.2	43.7	44.3	36.2	39.4	39.9	10.2
	9	42.5	39.3	43.4	40.1	39.3	39.2	43.6	44.2	36.2	39.3	39.6	43.5

Tension in Kips

Average Fastener Tension
(after snugging) = 8.6 Kips
(after tightening) = 40.9 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates (3mm gap)
Cal. Wrench Installation (with 12 kip Snug)
Tightened from Outside to Middle

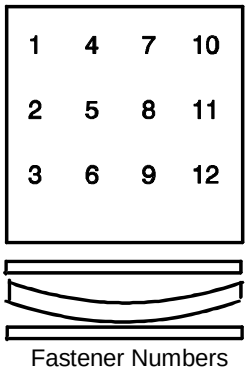


Figure B.76: Fastener Tensions for Test CD3CW122.OTM

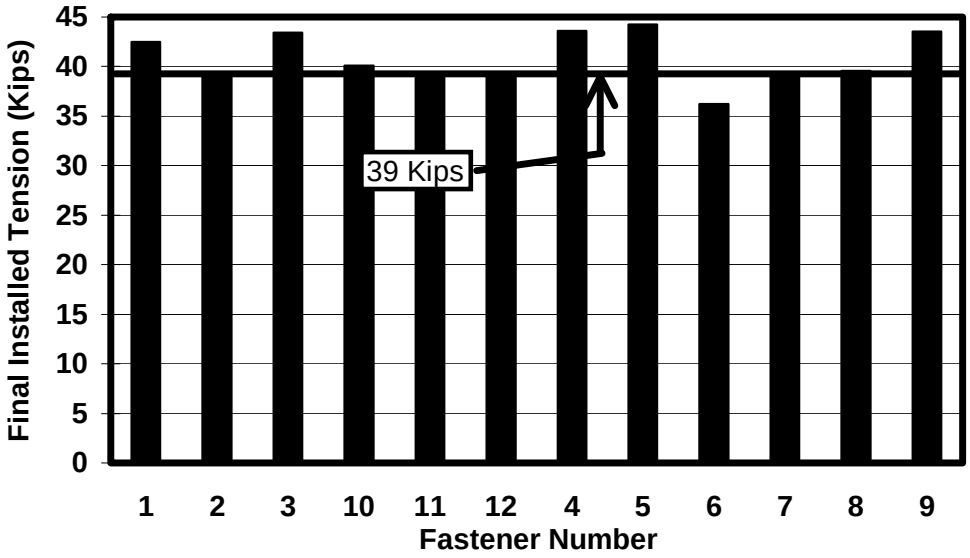


Figure B.77: **Final Installed Tensions for Test CD3CW122.OTM**

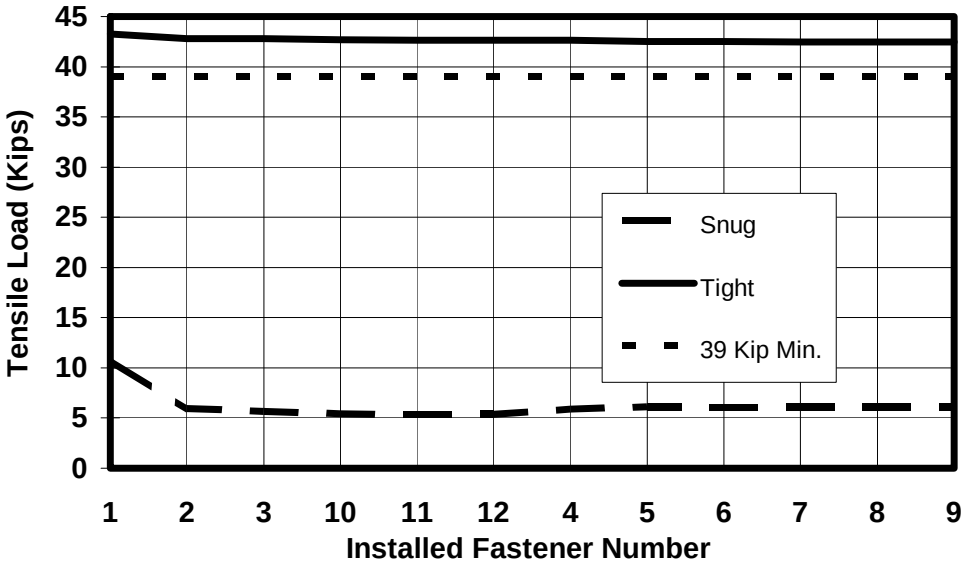


Figure B.78: **Tensile Load History for Fastener #1 - Test CD3CW122.OTM**

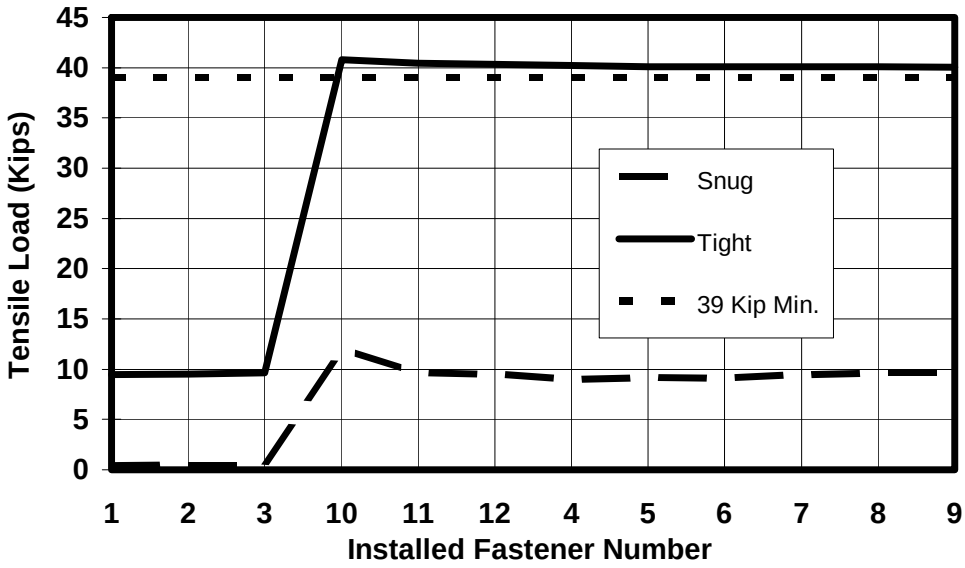


Figure B.79: **Tensile Load History for Fastener #10 - Test CD3CW122.OTM**

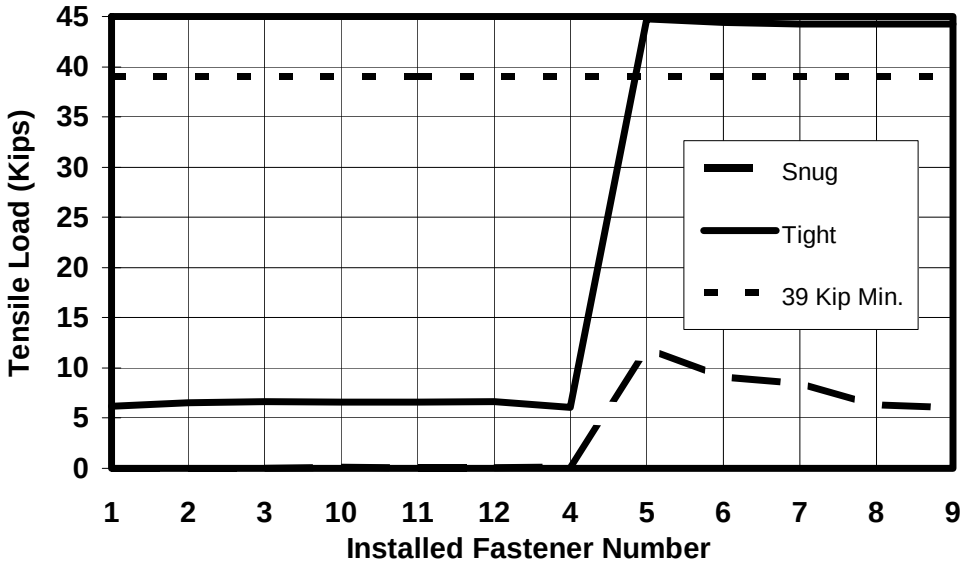


Figure B.80: **Tensile Load History for Fastener #5 - Test CD3CW122.OTM**

		Fastener Number											
		1	2	3	10	11	12	4	5	6	7	8	9
Snugging Order	1	11.4	0.0	0.0	1.3	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0
	2	7.7	12.5	0.0	1.6	0.1	1.2	0.1	0.0	0.1	0.0	0.0	0.0
	3	7.4	8.6	13.0	1.7	0.2	1.4	0.0	0.0	0.0	0.0	0.0	0.1
	10	6.9	6.7	12.3	9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11	7.0	5.7	11.8	2.5	11.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1
	12	7.0	5.1	11.6	3.9	0.9	12.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	3.7	3.6	11.1	2.8	0.8	11.4	11.5	0.0	0.1	0.0	0.0	0.0
	5	4.2	2.8	9.8	2.8	0.8	10.6	7.0	11.7	0.1	0.1	0.1	0.1
	6	4.3	3.3	7.4	2.8	0.9	9.4	7.1	6.4	11.3	0.0	0.1	0.1
	7	5.0	3.2	7.5	0.3	0.5	9.3	3.8	4.6	10.8	12.6	0.0	0.1
	8	5.1	3.3	7.7	0.2	0.2	7.8	3.5	2.7	8.6	9.8	13.1	0.1
	9	5.0	3.4	8.0	0.4	0.3	5.3	3.6	2.4	4.4	10.1	9.9	12.3
Tightening Order	1	39.6	3.0	8.8	0.0	0.3	5.4	3.3	2.9	4.7	10.2	9.8	11.8
	2	39.6	41.6	6.6	0.0	0.3	5.4	3.5	2.4	4.8	10.2	9.9	11.8
	3	39.5	41.7	45.3	0.0	0.2	5.6	3.5	2.7	3.4	10.3	9.9	12.0
	10	39.4	41.6	44.9	34.4	0.0	2.5	4.7	3.4	3.8	4.2	6.8	12.3
	11	39.3	41.5	44.6	33.8	42.7	0.1	4.8	3.7	4.6	4.7	5.5	10.9
	12	39.3	41.4	44.6	33.7	42.1	45.0	4.7	3.8	4.7	4.7	6.2	7.2
	4	39.5	41.5	44.5	33.8	42.0	44.8	38.4	2.2	4.6	1.9	4.8	7.3
	5	39.6	41.5	44.6	33.8	42.1	44.7	36.7	41.1	2.5	1.8	2.7	5.9
	6	39.6	41.6	44.8	33.8	42.1	44.5	36.7	39.9	37.7	1.8	2.4	3.0
	7	39.6	41.7	44.8	34.0	42.3	44.6	35.6	39.7	37.6	41.7	2.1	3.0
	8	39.5	41.6	44.8	34.0	42.3	44.5	35.6	38.6	36.9	41.5	42.4	2.4
	9	39.5	41.6	44.8	34.0	42.4	44.6	35.6	38.6	33.1	41.4	41.8	41.4

Tension in Kips

Average Fastener Tension
(after snugging) = 5.4 Kips
(after tightening) = 39.9 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates (3mm gap)
Cal. Wrench Installation (with 12 kip Snug)
Tightened from Outside to Middle

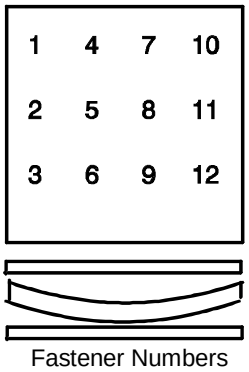


Figure B.81: Fastener Tensions for Test CD3CW123.OTM

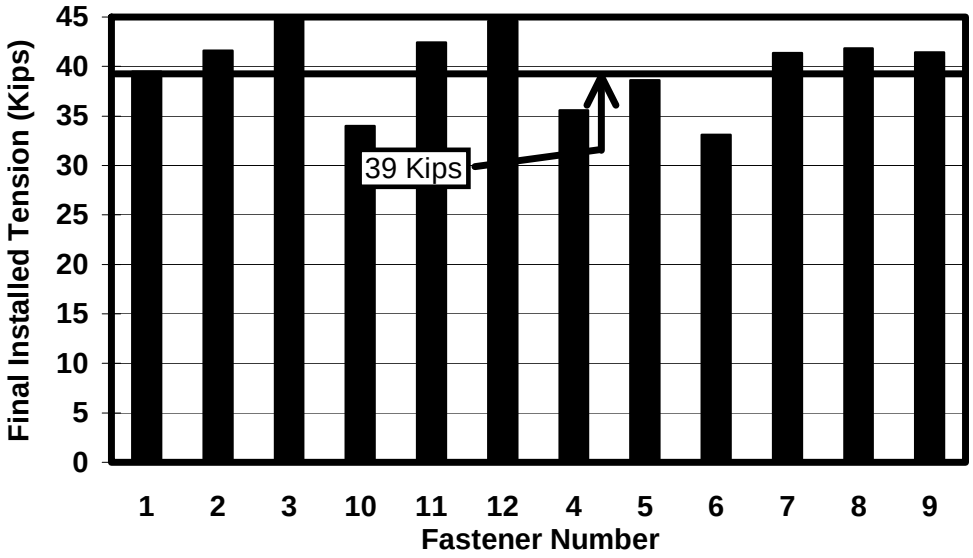


Figure B.82: **Final Installed Tensions for Test CD3CW123.OTM**

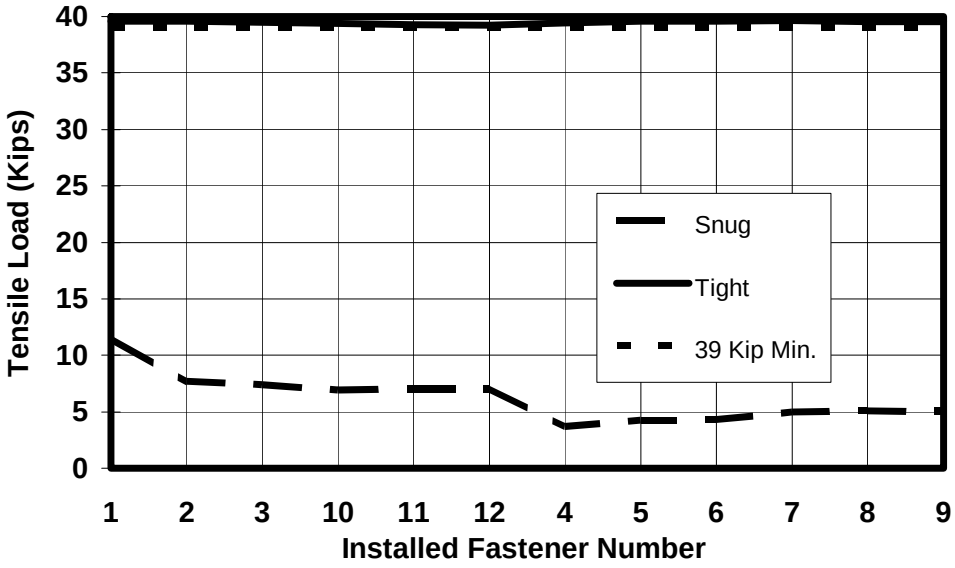


Figure B.83: **Tensile Load History for Fastener #1 - Test CD3CW123.OTM**

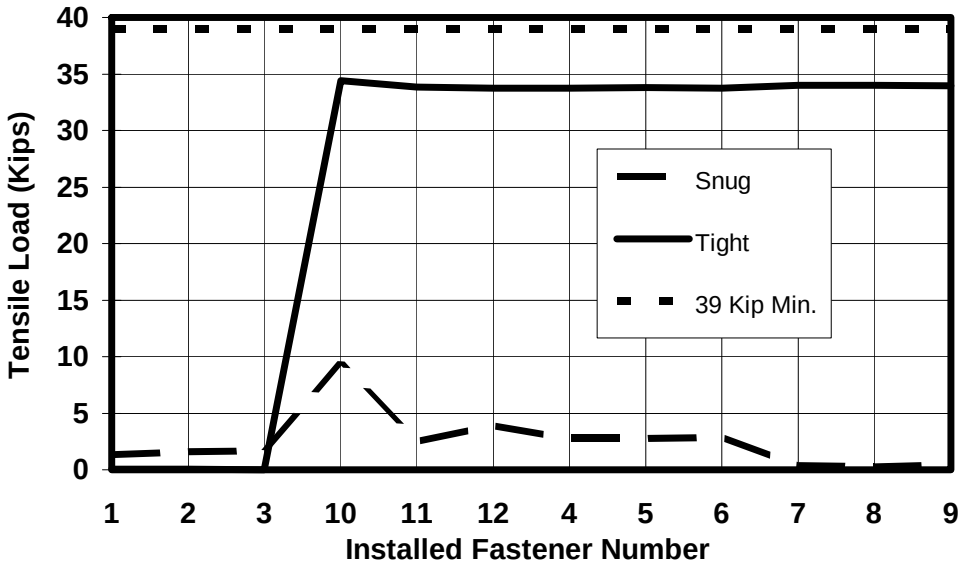


Figure B.84: **Tensile Load History for Fastener #10 - Test CD3CW123.OTM**

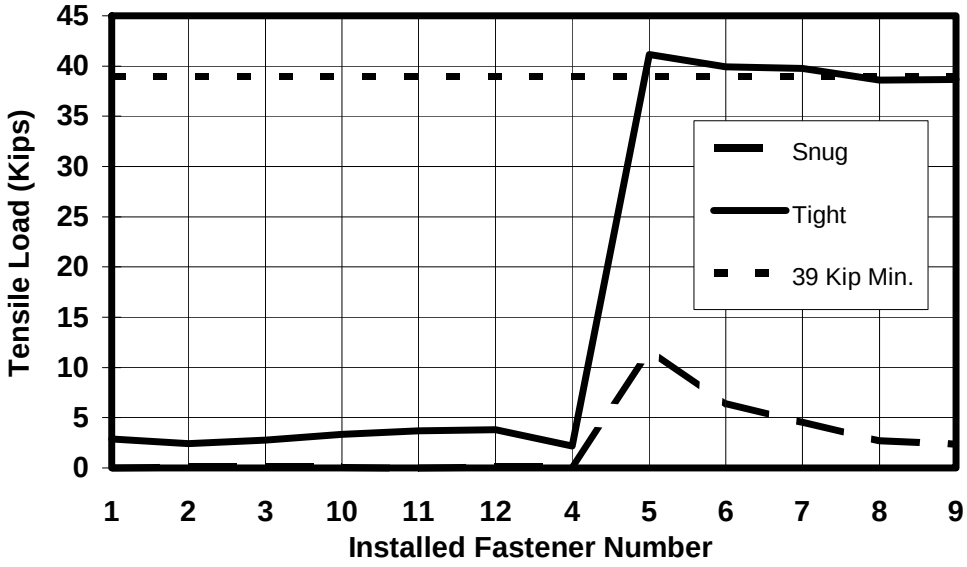


Figure B.85: **Tensile Load History for Fastener #5 - Test CD3CW123.OTM**

		Fastener Number											
		1	2	3	10	11	12	4	5	6	7	8	9
Snugging Order	1	11.0	0.0	0.0	2.8	0.5	2.7	-0.1	0.0	0.0	0.0	0.0	0.0
	2	4.6	12.2	0.0	3.2	0.9	3.4	0.0	0.0	0.0	0.0	0.0	0.0
	3	4.7	5.0	13.8	3.5	1.2	3.2	0.0	0.0	0.0	0.0	0.0	0.0
	10	4.5	5.0	14.0	11.5	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0
	11	5.1	5.0	13.6	3.3	11.6	0.0	-0.1	0.0	0.0	0.0	0.0	0.0
	12	5.4	5.5	13.4	3.6	1.5	12.4	0.0	0.0	0.0	0.0	0.0	0.0
	4	1.6	3.8	12.7	2.4	1.1	11.7	12.1	0.0	0.0	0.0	0.0	0.0
	5	1.8	2.6	10.1	2.4	0.9	10.6	6.0	12.4	0.0	0.0	0.0	0.0
	6	2.3	2.7	6.0	2.6	1.0	9.1	5.6	5.7	12.7	0.0	0.0	0.0
	7	2.9	3.5	6.8	0.3	0.2	8.7	1.6	3.1	11.3	12.6	0.0	0.0
	8	3.2	3.6	7.6	0.1	0.0	6.7	1.1	1.6	8.0	8.0	11.8	0.0
	9	3.4	4.2	8.1	0.3	0.0	3.3	1.1	1.0	2.6	8.2	6.4	14.2
Tightening Order	1	38.5	0.2	5.5	0.9	0.0	3.9	0.0	0.1	2.2	6.7	5.3	13.8
	2	34.6	43.9	0.4	1.0	0.0	4.6	-0.1	0.0	0.6	6.0	4.1	13.1
	3	34.7	40.0	45.1	1.2	0.1	5.6	0.0	0.0	0.1	6.0	3.9	8.8
	10	34.0	39.9	45.6	46.2	0.0	-0.1	-0.1	0.0	0.1	0.0	0.0	4.8
	11	33.5	39.1	44.8	37.5	41.4	-0.2	-0.2	-0.1	-0.1	-0.1	-0.2	0.2
	12	33.4	38.8	42.9	37.9	34.1	41.0	-0.3	-0.2	-0.2	-0.2	-0.2	-0.3
	4	31.3	37.8	42.8	36.2	33.4	40.5	42.6	-0.2	-0.2	-0.2	-0.2	-0.2
	5	31.8	37.7	41.5	36.0	33.2	39.6	38.3	39.9	-0.3	-0.2	-0.3	-0.3
	6	31.9	38.4	40.0	36.1	33.3	38.4	38.3	34.9	41.3	-0.2	-0.3	-0.3
	7	32.1	38.5	40.1	35.5	33.5	38.5	33.8	33.5	40.9	44.1	-0.2	-0.2
	8	32.1	38.5	40.1	35.8	33.4	38.3	33.6	31.5	39.3	41.4	42.6	-0.3
	9	32.0	38.5	40.2	35.7	33.6	37.9	33.6	31.3	34.3	41.4	40.7	44.3

Tension in Kips

Average Fastener Tension
(after snugging) = 4.4 Kips
(after tightening) = 37.0 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates (3mm gap)
Cal. Wrench Installation (with 12 kip Snug)
Tightened from Outside to Middle

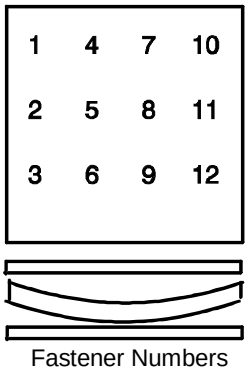


Figure B.86: Fastener Tensions for Test CD3CW124.OTM

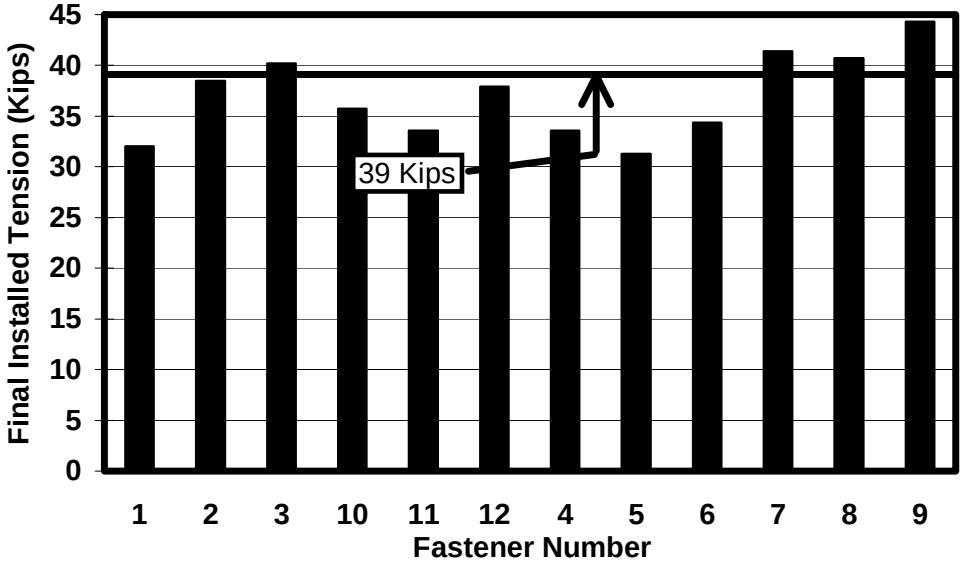


Figure B.87: **Final Installed Tensions for Test CD3CW124.OTM**

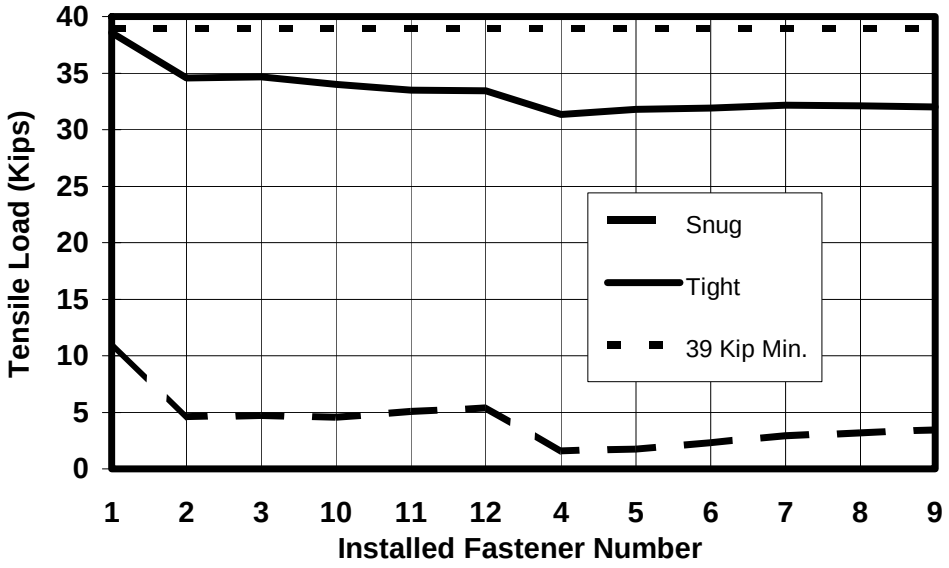


Figure B.88: **Tensile Load History for Fastener #1 - Test CD3CW124.OTM**

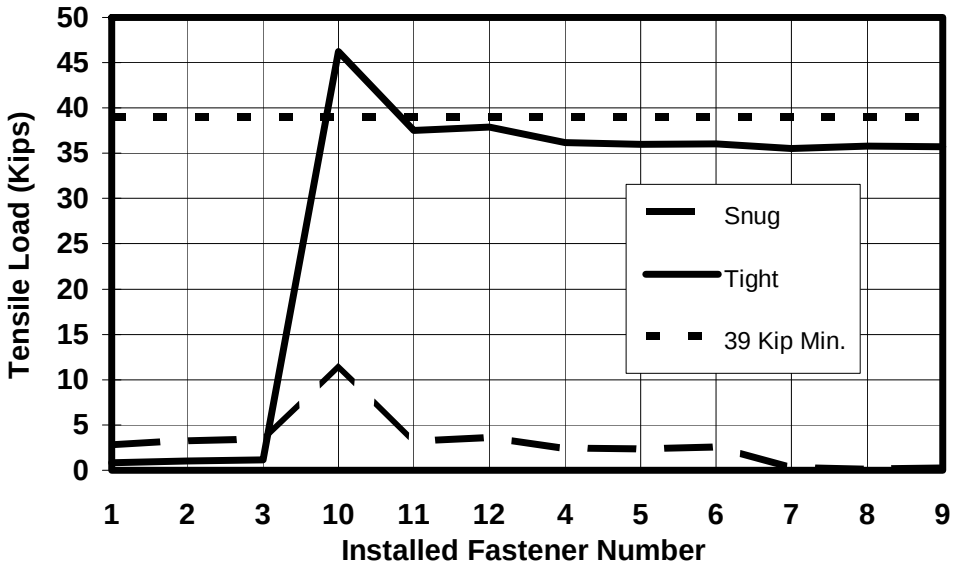


Figure B.89: **Tensile Load History for Fastener #10 - Test CD3CW124.OTM**

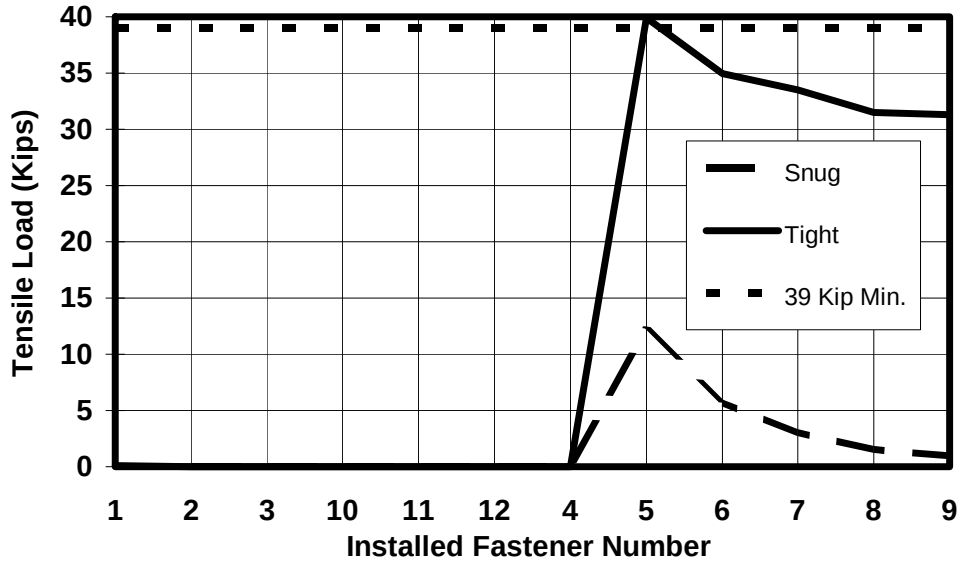


Figure B.90: **Tensile Load History for Fastener #5 - Test CD3CW124.OTM**

Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	13.3	0.0	0.0	0.1	-0.1	0.2	0.1	0.1	0.1	0.0	0.5	0.4
	5	3.9	10.9	0.1	0.2	0.0	0.2	0.1	0.1	0.0	-0.1	0.6	0.2
	6	4.8	2.1	10.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.8	0.1
	7	3.7	1.2	10.5	9.6	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.1
	8	4.3	0.6	9.6	5.2	8.0	0.2	0.1	0.1	0.0	-0.1	0.0	0.1
	9	4.9	0.9	6.6	4.7	3.0	14.1	0.2	0.1	0.1	-0.1	0.1	0.1
	1	0.6	0.0	3.7	5.9	3.4	14.1	11.0	0.1	0.0	0.0	0.0	0.1
	2	0.7	-0.1	1.3	5.6	3.4	14.5	5.4	12.8	0.0	-0.1	0.0	0.1
	3	0.7	0.1	0.9	5.7	3.5	14.7	5.4	10.2	9.1	0.0	0.0	0.1
	10	1.2	0.1	1.4	2.9	2.0	12.1	5.3	10.2	8.7	14.3	0.1	0.2
	11	1.3	0.1	1.7	2.9	1.7	9.0	5.2	10.2	8.7	9.4	12.9	0.1
	12	1.3	0.1	1.7	2.7	2.0	7.3	5.3	10.2	8.6	9.2	11.0	11.8
Tightening Order	4	24.4	0.0	1.7	1.2	0.6	7.3	6.2	10.5	8.5	9.4	10.9	11.1
	5	21.1	22.8	1.1	0.9	-0.2	5.7	6.3	11.4	8.7	9.5	11.0	11.2
	6	21.0	21.1	43.5	1.0	-0.3	2.6	6.3	11.4	9.4	9.4	11.1	11.2
	7	18.2	20.1	43.0	16.4	-0.2	2.8	6.3	11.3	9.3	8.9	11.1	11.2
	8	18.0	18.3	42.6	14.6	19.4	2.3	6.3	11.3	9.3	8.8	11.6	11.3
	9	18.1	18.5	42.1	14.5	17.9	47.6	6.2	11.3	9.4	8.8	11.7	12.0
	1	18.1	18.3	42.0	14.5	17.7	47.0	54.0	11.4	9.4	8.7	11.7	12.0
	2	18.0	18.6	42.0	14.6	17.7	46.9	53.4	55.7	9.8	8.7	11.7	11.9
	3	18.0	18.5	42.0	14.6	17.7	46.7	53.2	54.9	56.9	8.6	11.7	11.9
	10	18.1	18.6	42.0	14.5	17.6	46.6	53.1	54.8	56.3	54.8	11.9	11.9
	11	18.0	18.4	42.0	14.5	17.7	46.5	53.1	54.6	56.2	54.1	53.6	12.1
	12	18.0	18.4	41.9	14.4	17.8	46.3	52.9	54.5	56.1	54.0	52.9	54.8

Tension in Kips

Average Fastener Tension
(after snugging) = 5.9 Kips
(after tightening) = 40.2 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates (6mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Middle to Outside

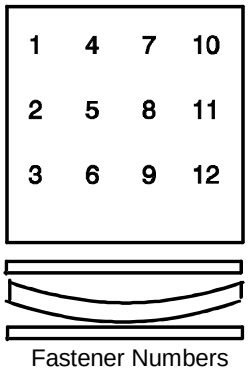


Figure B.91: Fastener Tensions for Test CD6TN122.MTO

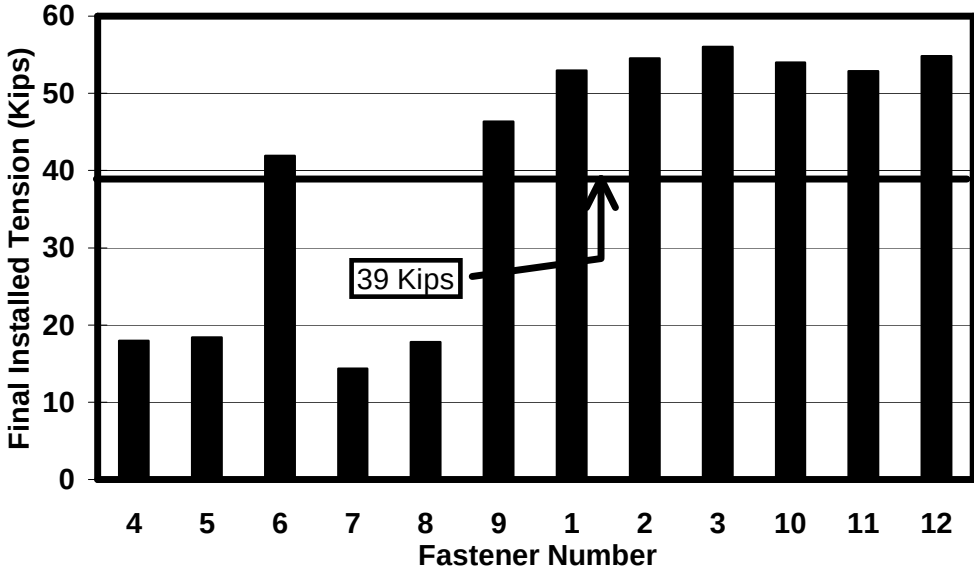


Figure B.92: **Final Installed Tensions for Test CD6TN122.MTO**

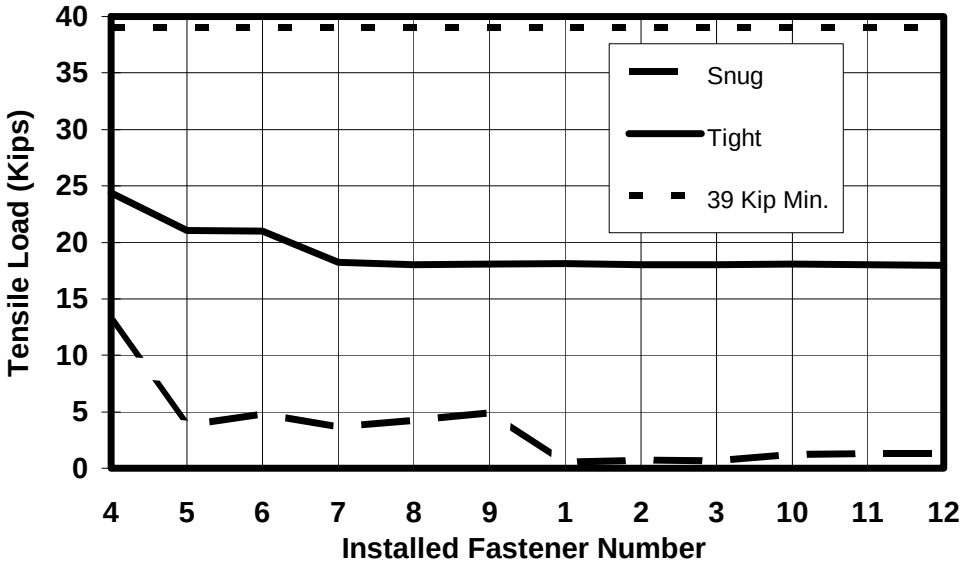


Figure B.93: **Tensile Load History for Fastener #4 - Test CD6TN122.MTO**

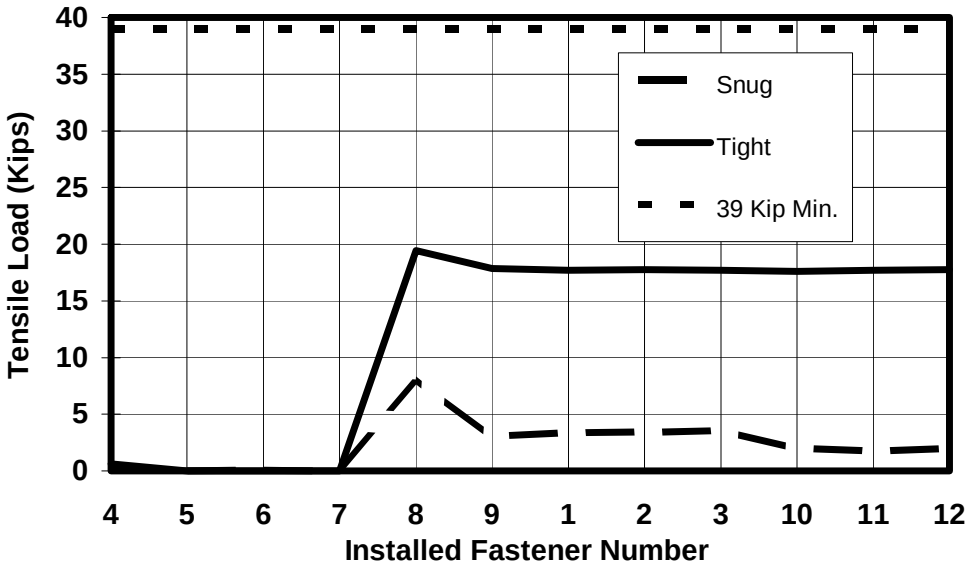


Figure B.94: **Tensile Load History for Fastener #8 - Test CD6TN122.MTO**

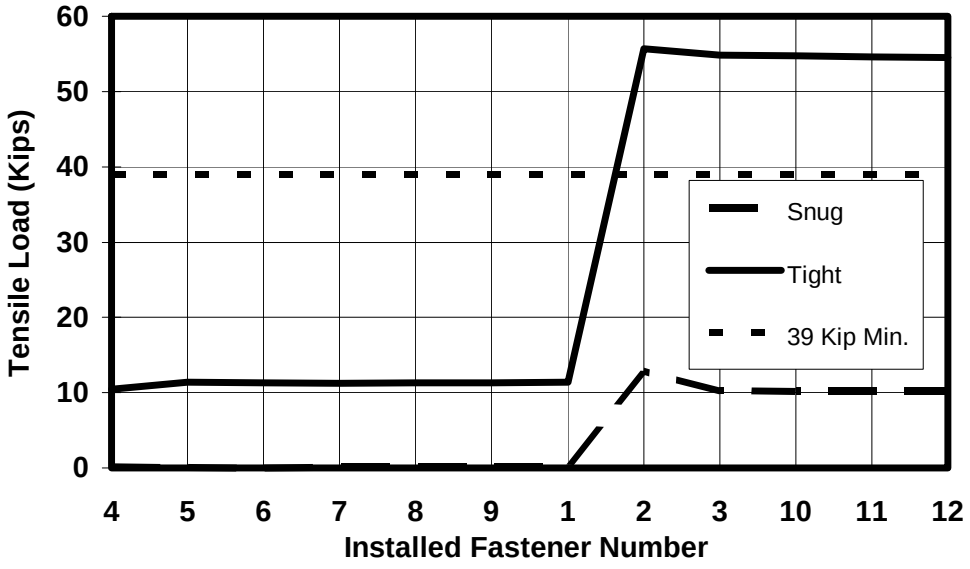


Figure B.95: **Tensile Load History for Fastener #2 - Test CD6TN122.MTO**

Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	12.3	-0.1	0.0	0.0	0.0	-0.1	0.0	-0.2	-0.4	0.3	0.2	0.8
	5	4.5	12.5	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	0.7	0.1	0.6
	6	5.2	5.0	9.3	-0.1	0.0	-0.1	-0.1	-0.1	-0.4	1.0	0.1	0.4
	7	0.6	2.1	9.0	11.8	-0.1	-0.1	0.1	-0.1	-0.3	-0.1	-0.2	0.0
	8	1.6	1.7	6.6	3.7	12.6	0.0	0.1	-0.1	-0.4	-0.2	-0.2	0.0
	9	2.5	2.8	3.3	3.9	3.8	11.6	0.0	-0.1	-0.3	-0.2	-0.3	-0.1
	1	0.0	0.1	-0.1	4.8	4.6	13.3	10.8	-0.2	-0.4	-0.2	-0.2	-0.1
	2	0.1	0.0	-0.1	5.2	4.7	12.8	2.7	10.8	-0.3	-0.1	-0.1	0.1
	3	0.1	0.0	0.0	5.4	5.2	12.1	3.2	2.0	9.8	-0.1	-0.2	0.2
	10	0.0	0.3	-0.1	0.3	2.4	11.4	5.3	3.0	10.8	9.0	-0.4	0.0
	11	0.0	0.4	0.0	1.0	0.8	7.2	5.8	3.0	12.2	3.9	10.7	0.0
	12	0.1	0.4	-0.1	1.7	1.3	2.5	5.6	3.0	12.9	4.7	2.1	11.8
1st Tightening Order	4	15.0	-0.1	-0.1	-0.2	-0.2	0.8	0.4	1.8	12.9	3.3	1.4	11.6
	5	10.4	8.6	-0.2	-0.4	-0.2	-0.2	0.5	1.2	11.3	3.2	1.1	11.2
	6	9.0	1.6	17.9	-0.2	-0.2	-0.2	1.1	1.4	4.2	3.3	1.4	8.1
	7	0.0	0.5	14.2	15.5	-0.2	-0.3	1.6	1.9	5.2	0.3	-0.2	8.5
	8	-0.1	0.1	4.7	2.3	25.8	-0.1	1.3	2.1	6.2	0.5	-0.6	4.0
	9	0.0	0.1	0.4	3.6	11.6	19.0	1.7	2.5	5.5	1.3	-0.5	0.8
	1	-0.1	-0.2	0.3	2.6	10.8	18.9	12.7	-0.2	3.3	2.3	-0.2	1.0
	2	-0.2	-0.4	0.0	2.8	10.1	18.3	4.3	14.6	-1.1	2.4	-0.3	1.2
	3	-0.1	-0.1	-0.2	2.9	10.2	16.6	5.1	3.2	12.5	2.4	-0.2	2.3
	10	0.0	0.0	-0.1	0.3	8.1	17.5	5.6	3.5	12.3	9.2	-0.8	1.1
	11	0.0	0.0	-0.1	0.7	5.7	15.2	5.9	3.4	12.8	4.6	10.3	-0.3
	12	0.0	0.0	-0.2	1.1	7.2	8.5	5.9	3.5	13.3	5.4	0.6	13.7
2d Tightening Order	4	20.7	-0.1	-0.2	-0.3	1.0	7.5	0.2	2.2	13.0	4.2	0.8	13.6
	5	12.6	25.0	-0.3	-0.3	-0.2	2.9	0.6	1.2	10.3	4.4	0.7	13.8
	6	13.2	16.0	24.9	-0.4	-0.3	-0.3	0.9	1.6	4.8	4.4	1.3	12.4
	7	6.4	13.0	23.8	38.5	-0.2	-0.3	2.0	2.3	5.2	-0.4	-0.6	12.9
	8	6.5	9.6	20.2	29.8	52.2	-0.4	2.2	2.5	5.7	-0.7	-0.8	7.2
	9	6.7	10.6	13.1	29.9	46.0	50.0	2.3	2.7	7.1	-0.6	-0.8	0.8
	1	3.7	9.6	13.5	29.7	45.7	48.9	40.9	-0.1	5.4	-0.6	-0.7	0.7
	2	4.1	9.4	12.7	29.8	45.5	48.9	40.7	43.4	1.1	-0.6	-0.6	0.8
	3	4.1	10.0	11.9	29.8	45.5	49.0	40.6	44.0	48.9	-0.6	-0.6	0.8
	10	4.7	10.1	11.9	20.2	41.0	47.4	40.4	43.8	48.3	7.0	-1.0	0.1
	11	4.7	10.3	12.4	20.3	38.9	43.7	40.6	43.8	48.2	3.5	9.3	-0.3
	12	4.7	10.2	12.7	20.7	38.9	37.8	40.4	43.7	48.0	3.5	0.9	18.0

Tension in Kips

Average Fastener Tension
(after snugging) = 3.8 Kips
(after 1st 1/2 turn) = 4.9 Kips
(after 2d 1/2 turn) = 23.3 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates (6mm gap)
Turn-of-Nut Installation (with 12 kip Snug)
Tightened from Middle to Outside

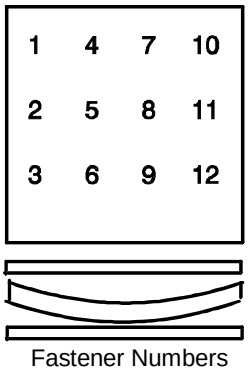


Figure B.96: Fastener Tensions for Test CD6TN123.MTO

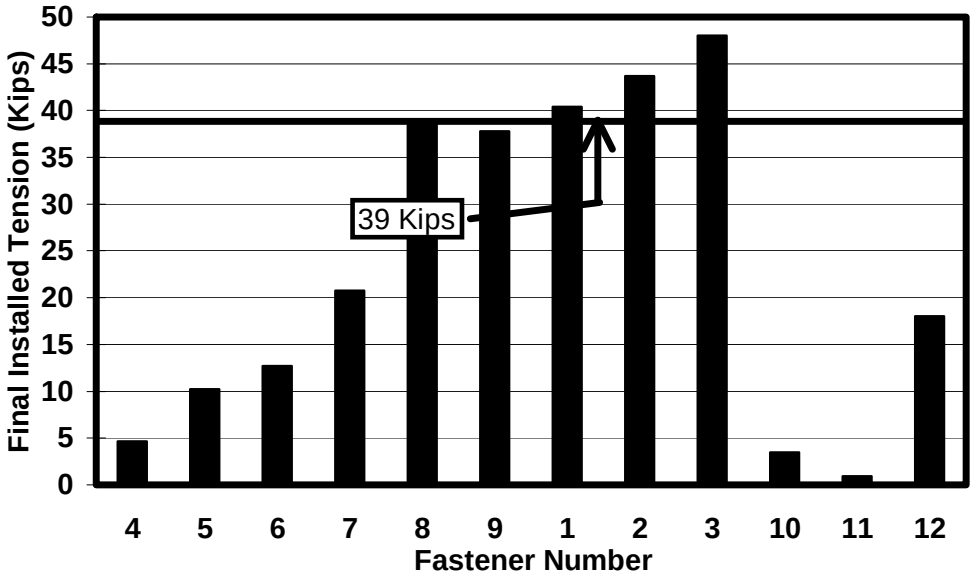


Figure B.97: **Final Installed Tensions for Test CD6TN123.MTO**

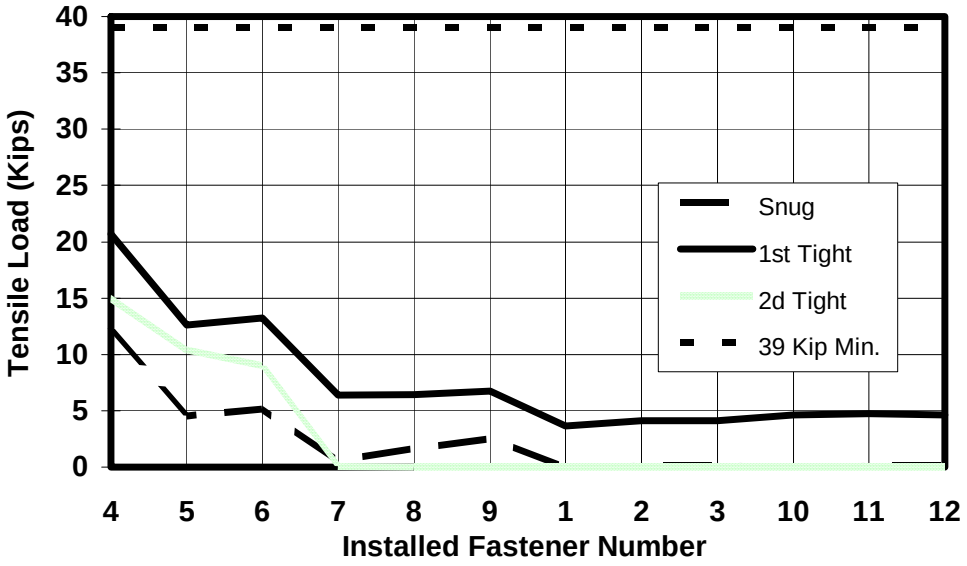


Figure B.98: **Tensile Load History for Fastener #4 - Test CD6TN123.MTO**

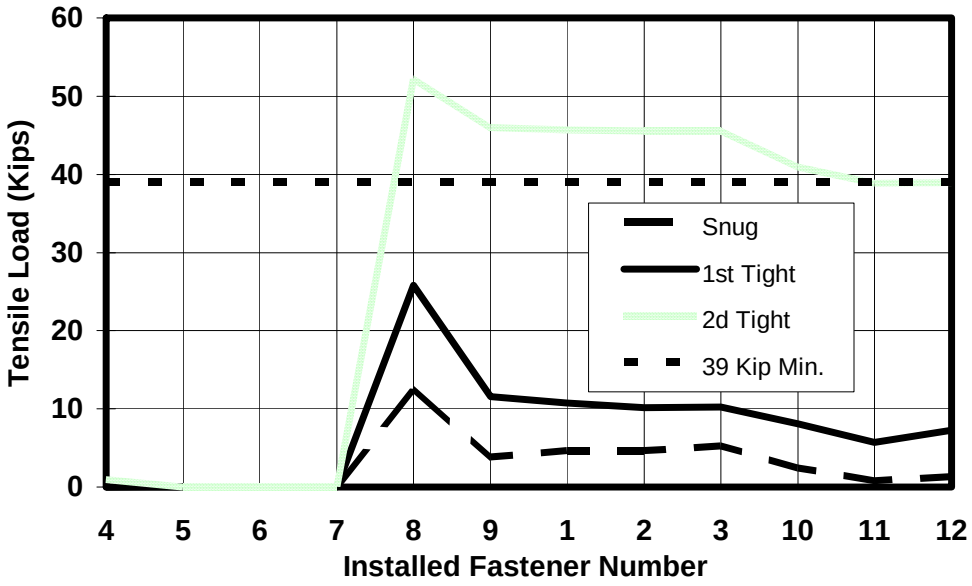


Figure B.99: **Tensile Load History for Fastener #8 - Test CD6TN123.MTO**

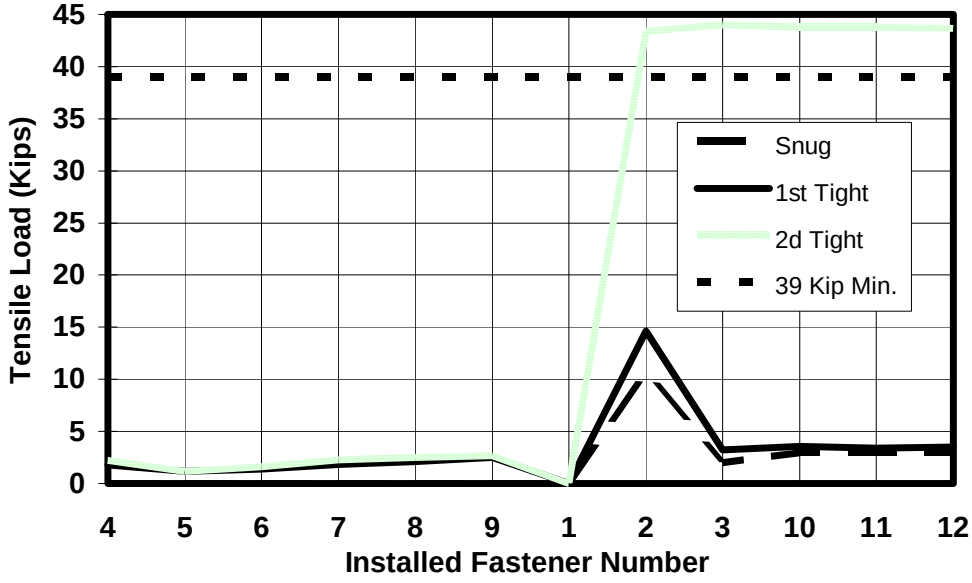


Figure B.100: **Tensile Load History for Fastener #2 - Test CD6TN123.MTO**

Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
25 K Snug Order	4	29.3	-0.1	-0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	2.1	1.2	0.9
	5	10.3	28.8	-0.2	0.0	0.0	0.0	-0.2	-0.1	-0.1	2.6	0.9	1.1
	6	11.2	7.7	27.0	0.1	0.1	0.1	-0.2	-0.1	-0.1	2.7	0.8	1.4
	7	1.6	4.6	26.2	23.3	0.0	0.0	-0.1	0.0	0.0	-0.2	0.0	-0.3
	8	2.8	3.2	19.6	7.6	26.9	0.0	-0.1	-0.1	0.0	-0.1	0.1	-0.5
	9	5.4	4.8	9.2	6.4	8.3	27.1	-0.2	-0.1	-0.1	-0.2	0.0	-0.5
	1	0.0	-0.4	0.5	10.0	10.6	31.6	22.4	-0.1	-0.1	-0.1	0.0	-0.5
	2	0.0	-0.6	0.0	11.8	10.4	30.9	5.1	23.3	-0.1	0.1	0.0	-0.4
	3	0.0	-0.6	0.3	12.6	11.1	28.6	4.8	2.9	28.1	0.3	-0.1	0.3
	10	0.0	-0.5	0.7	1.4	5.3	24.9	7.7	4.2	28.9	16.7	0.0	-0.5
	11	-0.1	-0.4	0.8	3.0	1.7	14.9	8.3	4.4	30.1	2.2	26.3	-0.5
	12	0.0	-0.7	0.9	5.4	2.7	4.4	8.1	4.7	30.4	2.7	4.1	27.9
Visual Snug Order	4	6.6	-1.3	1.1	4.6	4.8	7.5	7.2	6.9	41.4	3.4	5.2	26.3
	5	5.4	3.0	1.0	4.2	4.2	6.7	7.2	6.2	40.7	3.4	5.2	26.4
	6	5.2	2.2	8.4	4.1	3.7	4.4	7.3	6.0	38.7	3.6	5.3	26.3
	7	1.7	1.0	8.0	15.5	1.7	4.1	7.3	6.1	38.8	1.5	4.3	26.8
	8	1.1	0.1	6.3	11.0	16.1	2.2	7.3	5.6	38.4	1.4	2.8	25.6
	9	1.1	-0.2	3.5	11.0	11.3	16.9	7.5	5.7	36.6	1.7	3.0	22.0
	1	0.3	-0.5	3.7	10.4	11.0	16.7	16.8	3.4	36.4	1.9	3.3	22.1
	2	0.2	-0.7	3.3	10.0	10.1	16.3	15.1	23.9	35.1	1.9	3.3	22.1
	3	0.2	-0.8	2.5	10.0	9.8	14.7	15.0	22.9	52.9	1.9	3.3	22.1
	10	0.3	-0.5	2.7	7.2	9.0	15.2	15.2	22.9	52.6	8.1	1.5	21.2
	11	0.4	-0.5	2.8	7.0	6.8	14.8	15.2	23.0	52.6	4.2	14.0	15.3
	12	0.4	-0.5	3.1	8.0	7.0	10.2	15.2	23.1	52.7	4.0	5.8	27.7
Tightening Order	4	41.4	-1.5	2.2	0.4	2.8	8.9	9.5	19.0	52.1	3.9	5.7	27.3
	5	34.1	34.5	1.2	0.3	1.0	5.2	10.1	18.1	50.6	4.1	5.4	27.5
	6	33.8	26.2	49.3	0.3	0.8	0.5	10.1	19.2	48.7	4.2	5.7	26.8
	7	25.8	23.4	48.5	40.5	0.0	0.6	10.7	19.5	48.9	0.3	2.8	27.1
	8	25.5	20.6	46.4	32.0	49.9	0.0	10.8	19.6	48.9	0.0	0.7	21.7
	9	25.7	20.4	38.6	32.0	43.9	55.0	10.8	19.8	49.2	0.0	0.5	12.4
	1	25.8	20.6	38.7	32.0	43.7	54.3	54.2	19.7	49.3	0.0	0.5	12.6
	2	25.9	20.6	38.8	31.9	43.8	54.0	53.9	57.2	49.2	0.0	0.5	12.5
	3	25.9	20.6	38.7	31.9	43.6	53.9	53.9	56.8	52.8	0.1	0.5	12.5
	10	26.5	20.8	38.9	19.9	38.1	53.2	53.8	56.8	52.7	13.6	-0.1	8.2
	11	26.7	20.8	39.2	19.3	33.3	50.3	54.0	56.9	52.8	5.6	26.5	1.3
	12	26.7	20.7	39.1	20.1	33.8	48.3	53.9	56.9	52.8	5.3	12.8	54.4

Tension in Kips

Average Fastener Tension
(after snugging 25 kips) = 7.5 Kips
(after 2 x1/6 turn for vis. snug) = 13.0 Kips
(after tightening 1/2 turn) = 35.4 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates (6mm gap)
Turn-of-Nut Installation
(w/ 25 kip Snug then 1/3 turn total for visual plate contact)
Tightened from Middle to Outside

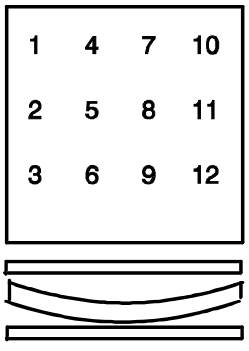


Figure B.101: Fastener Tensions for Test CD6TN254.MTO

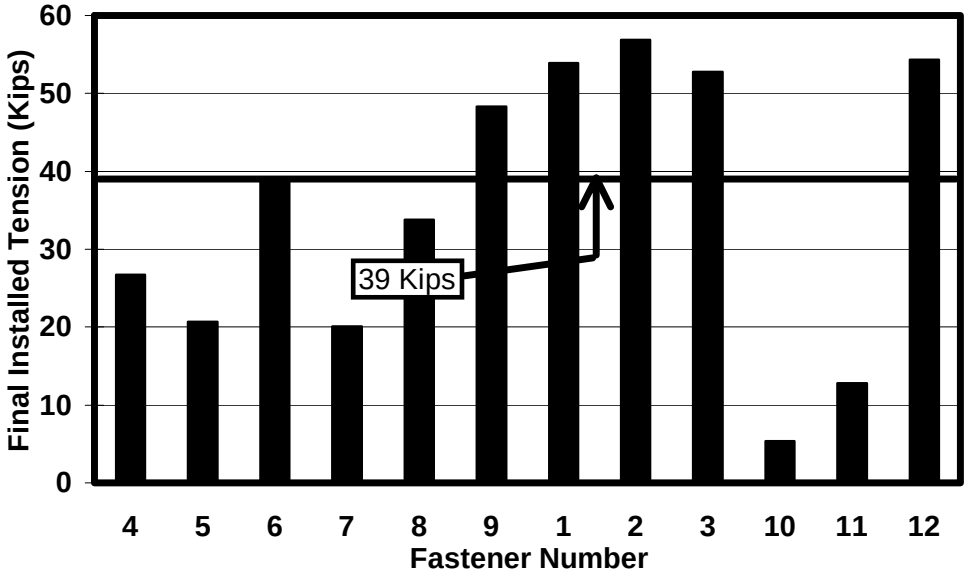


Figure B.102: **Final Installed Tensions for Test CD6TN254.MTO**

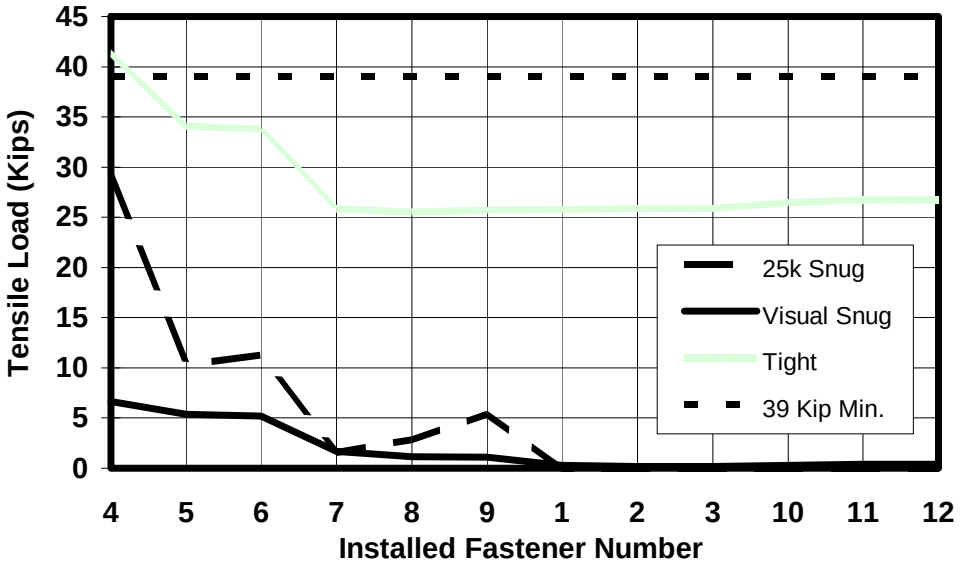


Figure B.103: **Tensile Load History for Fastener #4 - Test CD6TN254.MTO**

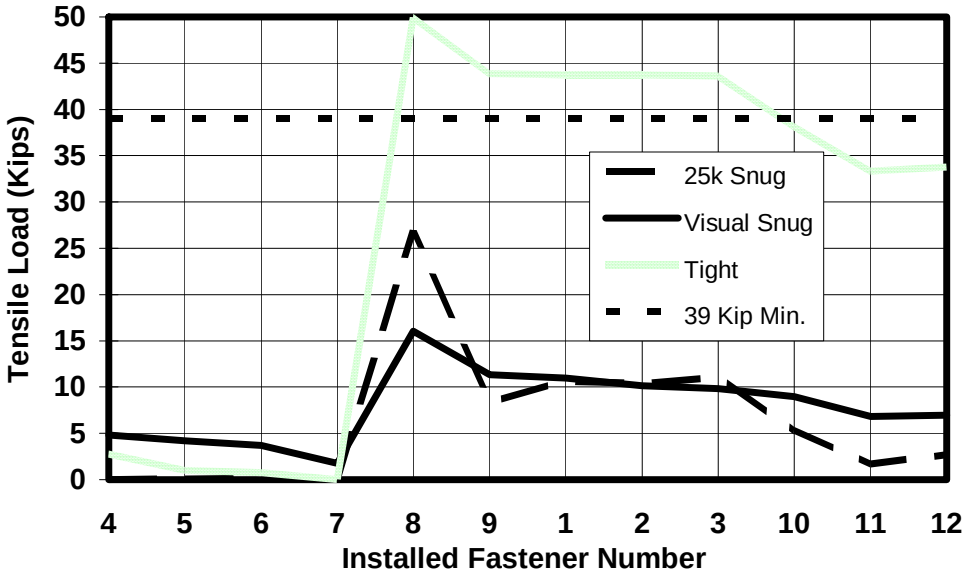


Figure B.104: **Tensile Load History for Fastener #8 - Test CD6TN254.MTO**

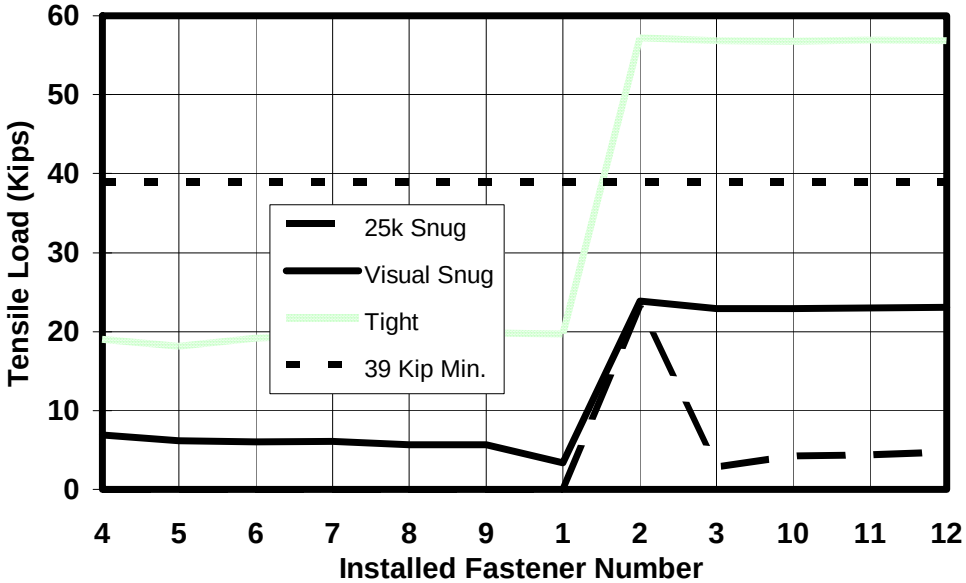


Figure B.105: **Tensile Load History for Fastener #2 - Test CD6TN254.MTO**

Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	12.3	-0.1	0.0	-0.1	0.0	0.0	0.0	0.0	-0.1	0.0	1.2	0.0
	5	5.7	11.2	0.2	-0.2	-0.1	-0.2	-0.1	-0.1	-0.1	0.0	1.1	0.1
	6	6.1	3.0	12.0	-0.1	0.0	0.0	0.0	0.0	-0.1	-0.1	1.2	0.1
	7	0.7	0.9	10.1	10.3	-0.1	-0.1	-0.1	0.0	0.0	-0.1	-0.3	0.0
	8	1.5	0.6	6.4	2.9	12.5	-0.1	-0.1	0.0	-0.1	-0.1	-0.3	0.0
	9	2.8	1.3	2.8	3.1	3.0	11.5	-0.1	0.0	-0.1	-0.1	-0.3	0.0
	1	-0.1	0.0	-0.1	4.3	4.7	12.4	9.6	0.0	-0.1	-0.1	-0.3	0.1
	2	-0.1	0.1	0.0	4.8	5.3	11.3	1.7	11.2	-0.1	-0.1	-0.3	0.0
	3	-0.1	-0.1	-0.1	4.8	6.2	10.2	1.8	1.5	11.1	0.0	-0.3	0.2
	10	0.0	0.1	-0.1	0.0	0.9	9.8	3.1	2.3	12.0	10.3	-0.4	-0.1
	11	-0.1	0.1	-0.1	0.7	0.3	7.2	3.2	2.4	12.9	3.5	8.3	0.0
	12	-0.1	0.0	-0.1	1.4	0.5	2.9	3.2	2.5	13.9	4.2	0.7	11.6
Tightening Order	4	38.5	-0.3	-0.3	-0.7	-0.4	-0.4	-0.3	-0.2	8.4	1.8	0.2	10.2
	5	22.4	42.3	-0.1	-0.7	-0.3	-0.3	-0.2	-0.2	2.3	2.0	0.2	7.5
	6	23.4	25.0	41.3	-0.6	-0.3	-0.3	-0.3	-0.4	-0.6	2.3	0.6	6.2
	7	22.5	24.2	39.4	43.7	-0.3	-0.5	-0.1	-0.4	0.1	-0.3	-1.1	5.5
	8	23.3	22.7	36.1	33.2	42.5	-0.4	0.1	-0.2	1.2	-0.4	-1.0	1.2
	9	23.4	24.1	30.9	32.0	29.4	43.7	0.0	0.1	2.5	-0.4	-0.8	-0.4
	1	10.3	16.0	27.8	32.0	29.0	42.7	41.3	-0.4	-0.6	-0.4	-0.8	-0.4
	2	10.9	14.9	21.4	31.9	28.9	43.3	36.9	40.8	-0.6	-0.4	-0.8	-0.4
	3	10.8	15.8	19.5	31.9	28.9	43.6	37.2	37.3	40.3	-0.3	-0.7	-0.4
	10	11.5	16.2	20.0	18.5	16.8	36.0	37.2	37.2	39.6	44.1	-0.6	-0.4
	11	11.4	16.2	20.3	19.1	15.1	30.0	37.2	37.2	39.5	40.4	36.3	-0.3
	12	11.4	16.3	20.6	19.3	16.0	27.8	37.2	37.2	39.4	40.5	31.7	50.6
Touch-up Order	4	42.2	16.2	20.6	17.8	15.8	27.9	37.2	37.1	39.1	40.4	31.7	49.6
	5	41.7	39.3	20.5	17.8	15.2	27.9	37.3	37.1	39.1	40.4	31.7	49.6
	6	41.7	38.8	41.2	17.8	15.2	27.2	37.3	37.1	39.1	40.4	31.7	49.6
	7	40.6	38.5	40.7	42.7	14.9	27.0	37.1	37.0	39.0	40.4	31.6	49.4
	8	40.6	37.8	40.6	42.1	42.6	27.2	37.2	37.1	39.1	40.5	31.8	49.5
	9	40.6	37.8	39.5	41.9	42.2	44.1	37.1	37.0	39.0	40.4	31.8	49.5
	1	40.5	37.6	39.4	41.8	42.0	43.8	41.9	37.0	38.9	40.4	31.8	49.4
	2	40.5	37.6	39.4	41.8	41.8	43.8	41.8	41.9	39.0	40.4	31.8	49.5
	3	40.5	37.6	39.5	41.7	41.9	43.7	41.7	41.9	43.8	40.4	31.7	49.4
	10	40.5	37.4	39.4	41.5	41.7	43.4	41.5	41.6	43.4	46.2	31.7	49.3
	11	40.5	37.4	39.4	41.4	41.7	43.4	41.5	41.6	43.3	46.0	36.2	49.4
	12	40.5	37.5	39.4	41.6	41.7	43.6	41.6	41.6	43.4	46.0	36.2	51.0

Tension in Kips

Average Fastener Tension
(after snugging) = 3.4 Kips
(after tightening) = 29.0 Kips
(after touch-up) = 42.0 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates (6mm gap)
Cal. Wrench Installation (with 12 kip Snug)
Tightened from Middle to Outside

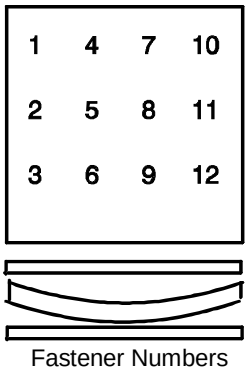


Figure B.106: Fastener Tensions for Test CD6CW123.MTO

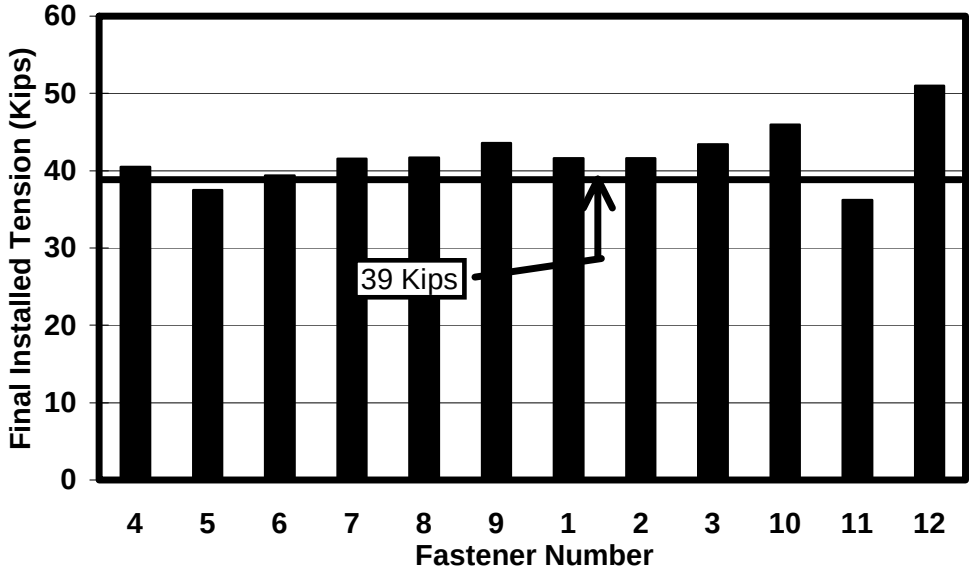


Figure B.107: **Final Installed Tensions for Test CD6CW123.MTO**

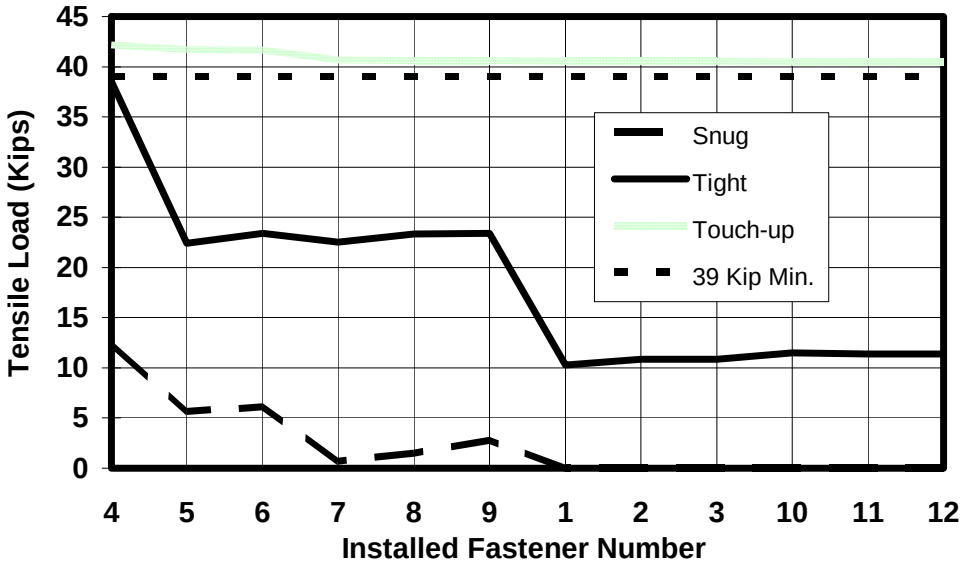


Figure B.108: **Tensile Load History for Fastener #4 - Test CD6CW123.MTO**

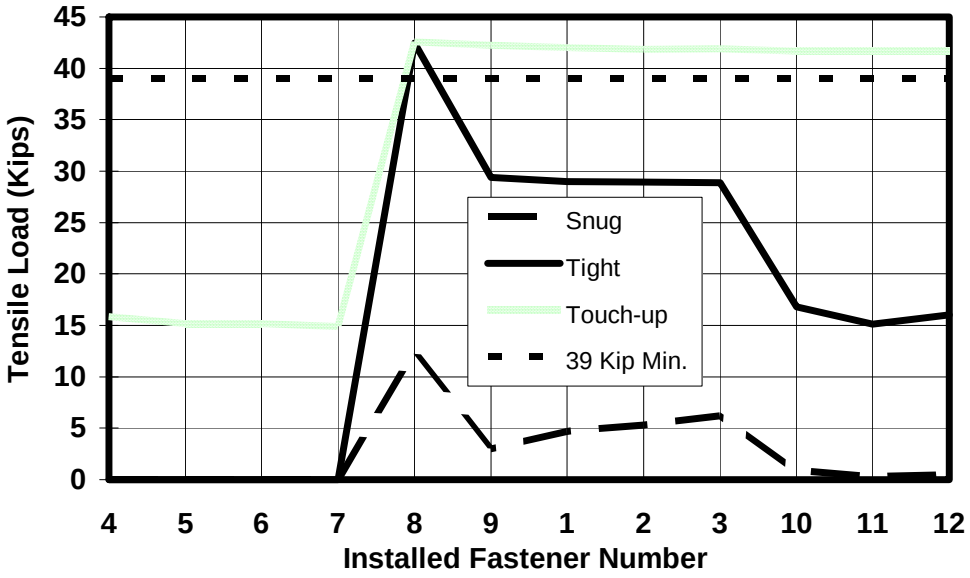


Figure B.109: **Tensile Load History for Fastener #8 - Test CD6CW123.MTO**

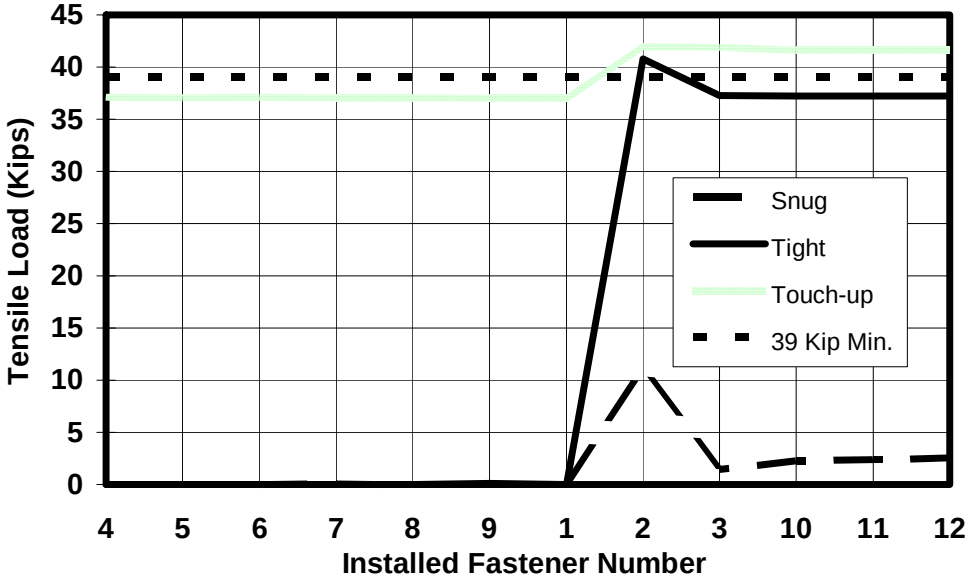


Figure B.110: **Tensile Load History for Fastener #2 - Test CD6CW123.MTO**

Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	11.2	-0.2	-0.8	0.1	-0.3	0.1	0.0	-0.1	0.2	-0.6	0.0	1.3
	5	4.0	11.2	-0.8	0.1	-0.2	0.1	0.0	-0.1	0.0	-0.8	0.2	1.3
	6	3.8	3.1	12.3	0.0	-0.2	0.1	0.0	-0.1	0.0	-0.7	0.2	1.4
	7	1.4	0.7	14.2	14.1	-0.1	0.1	-0.1	0.0	-0.1	-0.1	-0.2	-0.5
	8	2.5	0.2	11.9	6.0	11.9	0.1	0.0	0.0	-0.1	-0.1	-0.1	-0.4
	9	4.2	0.8	8.6	4.9	3.9	11.9	-0.1	-0.1	-0.3	-0.1	0.0	-0.4
	1	0.0	-0.2	1.9	6.7	5.8	16.1	11.1	0.0	-0.2	0.0	0.0	-0.5
	2	0.0	-0.2	-0.5	7.8	6.1	16.3	2.3	12.8	-0.1	0.0	0.0	-0.4
	3	0.0	-0.2	-0.8	8.5	6.9	15.1	2.3	2.9	12.6	-0.1	0.0	-0.4
	10	0.0	-0.4	-0.6	1.7	2.9	12.8	3.9	4.5	14.7	11.6	0.0	-0.4
	11	0.0	-0.4	-0.3	2.5	1.1	8.6	4.0	4.7	15.9	3.8	12.5	-0.5
	12	0.1	-0.4	-0.2	3.3	1.5	3.8	4.1	5.2	16.9	3.9	3.8	12.5
Tightening Order	4	36.4	-0.1	-0.6	0.2	-0.1	0.2	0.0	-0.1	11.6	1.7	2.6	12.7
	5	10.8	39.7	-0.8	0.2	-0.2	0.1	0.0	-0.1	2.8	1.7	2.2	9.3
	6	11.5	9.5	45.6	0.2	-0.1	0.1	0.1	-0.1	-0.3	2.4	3.1	7.1
	7	2.1	2.9	41.8	46.7	-0.2	0.0	1.9	0.8	0.6	-0.2	-0.1	4.1
	8	2.7	2.1	39.0	34.1	42.1	0.1	2.5	1.6	1.7	-0.2	-0.2	0.0
	9	3.3	3.6	35.1	32.4	29.9	41.6	3.0	2.6	3.8	-0.2	-0.1	-0.6
	1	-0.1	0.2	25.7	35.9	32.5	44.1	37.8	-0.1	-0.4	-0.3	-0.2	-0.5
	2	-0.1	0.0	13.2	36.0	33.2	46.3	20.5	46.7	-0.3	-0.3	-0.1	-0.5
	3	-0.1	0.8	10.0	35.9	33.2	46.6	21.0	38.6	44.0	-0.3	-0.2	-0.5
	10	0.1	1.2	11.7	16.7	17.8	35.1	21.1	38.7	43.3	40.3	-0.1	-0.3
	11	0.1	1.1	13.2	18.3	13.3	24.4	21.2	38.8	43.2	24.1	41.5	-0.2
	12	0.1	1.1	13.3	18.7	14.5	19.3	21.2	38.8	43.2	25.5	33.3	46.4
Touch-up Order	4	34.0	0.5	13.3	14.7	13.4	19.5	21.0	39.2	43.0	25.7	33.3	45.4
	5	33.0	34.6	12.7	14.3	12.0	19.1	21.2	39.2	43.1	25.7	33.3	45.4
	6	32.8	33.8	38.0	14.6	11.9	16.6	21.1	39.2	42.8	25.6	33.3	45.2
	7	31.1	33.7	37.9	44.3	11.3	16.6	21.3	39.4	42.9	25.6	33.4	45.3
	8	31.0	33.1	37.8	43.5	35.9	15.9	21.3	39.4	42.9	25.7	33.4	45.4
	9	31.0	33.0	35.9	43.4	35.3	42.1	21.3	39.4	43.0	25.7	33.4	45.1
	1	30.9	33.0	35.8	43.2	35.1	41.8	34.0	39.3	42.9	25.7	33.4	45.0
	2	30.9	32.9	35.8	43.2	35.1	41.7	33.8	43.3	42.9	25.7	33.4	45.1
	3	30.9	32.9	35.8	43.2	35.2	41.7	33.9	43.3	45.1	25.8	33.5	45.1
	10	30.9	32.9	35.7	43.0	35.1	41.6	33.7	43.2	44.9	38.7	33.4	45.0
	11	30.9	32.9	35.7	43.0	35.1	41.6	33.7	43.2	44.8	38.5	41.7	45.0
	12	30.9	32.8	35.7	43.0	35.0	41.6	33.7	43.2	44.8	38.3	41.5	46.6

Tension in Kips

Average Fastener Tension
(after snugging) = 4.5 Kips
(after tightening) = 23.0 Kips
(after touch-up) = 38.9 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates (6mm gap)
Cal. Wrench Installation (with 12 kip Snug)
Tightened from Middle to Outside

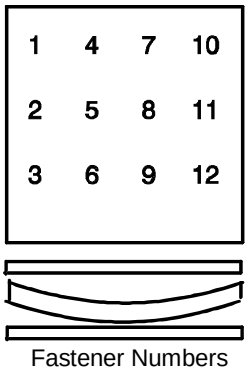


Figure B.111: Fastener Tensions for Test CD6CW124.MTO

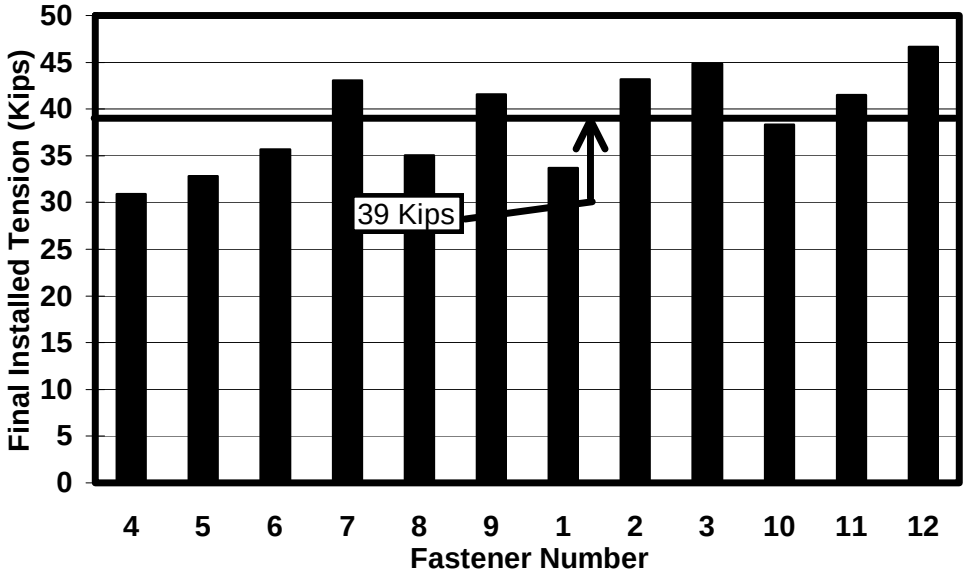


Figure B.112: **Final Installed Tensions for Test CD6CW124.MTO**

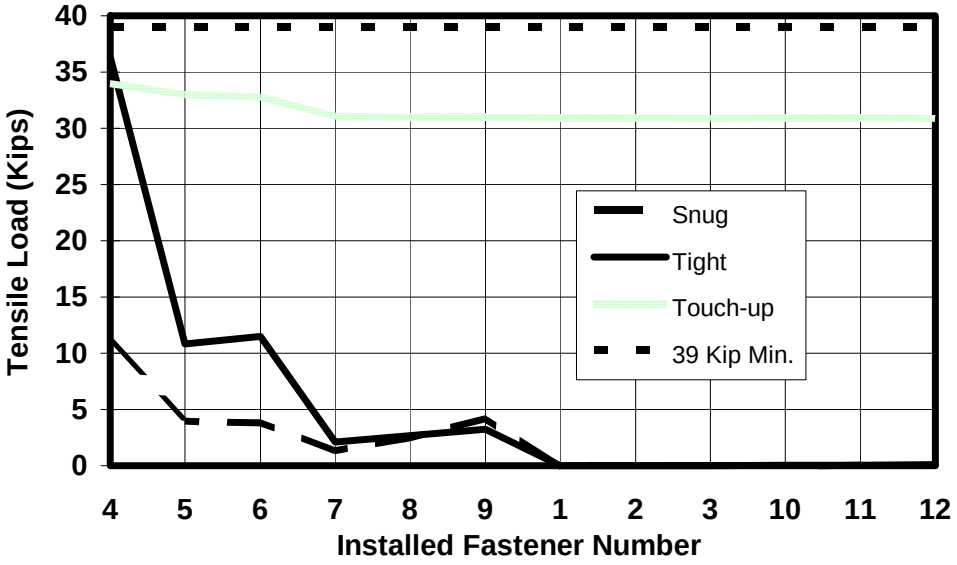


Figure B.113: **Tensile Load History for Fastener #4 - Test CD6CW124.MTO**

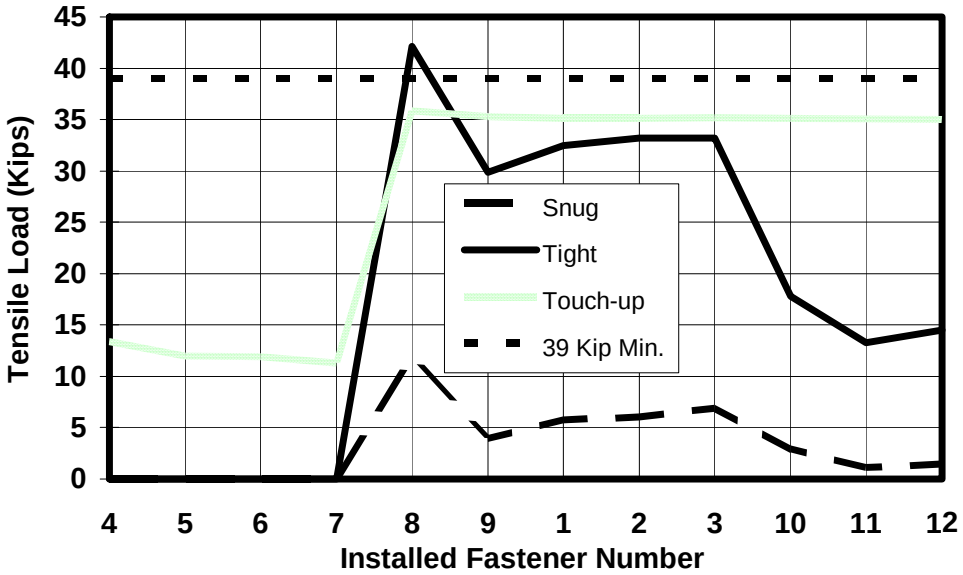


Figure B.114: **Tensile Load History for Fastener #8 - Test CD6CW124.MTO**

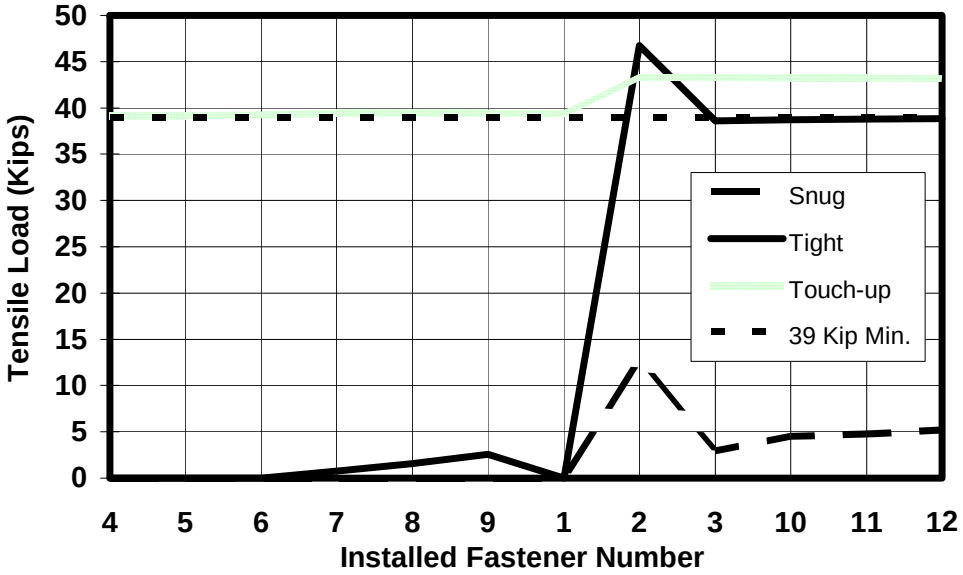


Figure B.115: **Tensile Load History for Fastener #2 - Test CD6CW124.MTO**

Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	24.9	-0.1	-0.7	-0.1	0.0	-0.1	-0.1	0.1	-0.2	-0.2	1.2	1.8
	5	3.7	27.1	-0.1	-0.1	0.1	0.1	0.1	0.0	-0.1	-0.3	1.8	1.7
	6	5.1	6.8	28.7	-0.1	0.1	0.0	0.1	0.1	-0.1	-0.2	2.2	1.3
	7	1.3	1.9	26.9	25.5	0.0	0.0	0.1	0.1	-0.2	-0.2	-0.1	-0.1
	8	2.8	1.8	19.1	10.0	26.3	0.0	0.0	0.1	-0.2	-0.2	-0.1	-0.1
	9	4.3	3.5	13.1	9.8	11.7	25.7	0.1	0.1	-0.1	-0.1	0.0	0.0
	1	-0.1	-0.4	10.3	13.8	14.9	29.1	24.0	0.0	-0.3	-0.4	0.0	-0.1
	2	-0.1	-0.2	6.8	13.8	15.3	30.5	7.5	27.7	-0.2	-0.3	0.0	-0.1
	3	0.0	-0.2	5.5	13.9	15.3	30.1	8.4	17.4	27.2	-0.4	0.0	-0.1
	10	0.0	-0.2	15.1	3.6	7.3	23.8	8.6	17.5	26.7	20.5	0.0	-0.1
	11	0.0	-0.1	12.7	3.9	5.0	16.3	8.6	17.3	26.8	8.0	15.2	-0.1
	12	0.0	-0.1	11.3	4.7	5.7	8.8	8.6	17.4	27.0	7.7	0.0	29.5
Tightening Order	4	38.9	-0.3	BG	1.2	3.4	8.9	8.8	17.6	26.8	7.6	0.3	28.7
	5	35.8	43.5	BG	0.9	1.3	6.7	9.0	17.8	26.6	7.6	0.3	28.7
	6	35.9	41.8	BG	1.1	1.2	3.6	9.0	18.0	25.7	7.6	0.4	28.5
	7	33.0	40.9	BG	42.1	0.7	3.5	8.9	17.9	25.6	3.1	-0.1	28.5
	8	33.0	39.4	BG	41.2	43.7	3.1	8.9	18.0	25.7	3.4	-0.1	28.6
	9	33.0	39.1	BG	41.0	42.9	42.2	8.9	18.0	25.7	3.4	-0.2	28.9
	1	33.2	39.3	BG	40.9	42.8	41.9	41.7	18.3	25.8	3.4	-0.1	28.9
	2	33.3	39.3	BG	41.0	42.7	41.8	41.4	44.0	26.2	3.4	-0.1	28.8
	3	33.3	39.3	BG	40.8	42.7	41.6	41.3	44.1	46.3	3.5	-0.2	28.8
	10	33.4	39.4	BG	39.6	42.6	41.6	41.3	44.0	46.1	39.2	-0.2	29.1
	11	33.4	39.4	BG	39.7	42.4	41.6	41.2	43.9	45.9	38.7	38.8	29.5
	12	33.4	39.4	BG	39.9	42.4	41.7	41.2	43.8	45.8	38.6	38.7	44.6
Touch-up Order	4	38.1	39.2	BG	39.8	42.2	41.4	40.9	43.3	45.3	38.4	38.1	44.1
	5	38.0	41.0	BG	39.6	42.2	41.3	40.8	43.3	45.2	38.4	38.1	44.0
	6	38.0	40.9	BG	39.8	42.2	41.3	40.9	43.3	45.3	38.5	38.1	44.1
	7	37.9	40.7	BG	43.5	42.1	41.2	40.8	43.2	45.1	38.3	38.0	43.9
	8	37.8	40.7	BG	43.2	45.7	41.1	40.8	43.2	45.2	38.4	38.0	44.0
	9	37.8	40.7	BG	43.2	45.6	44.8	40.7	43.2	45.2	38.3	38.0	43.9
	1	37.8	40.8	BG	43.2	45.5	44.7	44.1	43.2	45.1	38.4	38.0	44.0
	2	37.7	40.6	BG	43.1	45.5	44.6	44.0	46.3	45.1	38.4	38.0	44.0
	3	37.7	40.7	BG	43.3	45.4	44.7	44.0	46.2	48.2	38.3	38.0	43.9
	10	37.8	40.8	BG	43.2	45.5	44.6	44.0	46.3	48.1	43.5	38.0	44.0
	11	37.7	40.6	BG	43.0	45.3	44.2	43.7	45.9	47.7	43.2	40.9	43.9
	12	37.7	40.7	BG	43.0	45.3	44.3	43.8	45.9	47.7	43.2	40.9	46.6

Tension in Kips

Average Fastener Tension
(after snugging) = 10.0 Kips
(after tightening) = 40.9 Kips
(after touch-up) = 43.6 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates (6mm gap)
Cal. Wrench Installation (with 25 kip Snug)
Tightened from Middle to Outside

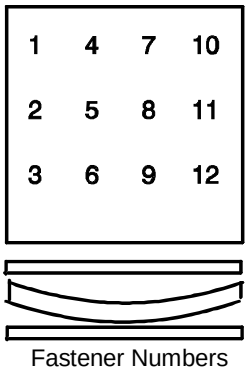


Figure B.116: Fastener Tensions for Test CD6CW253.MTO

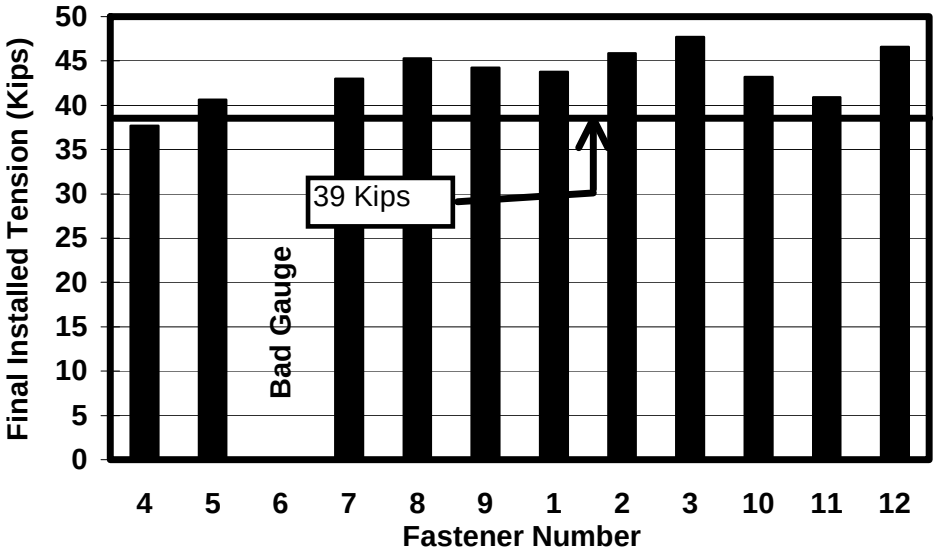


Figure B.117: **Final Installed Tensions for Test CD6CW253.MTO**

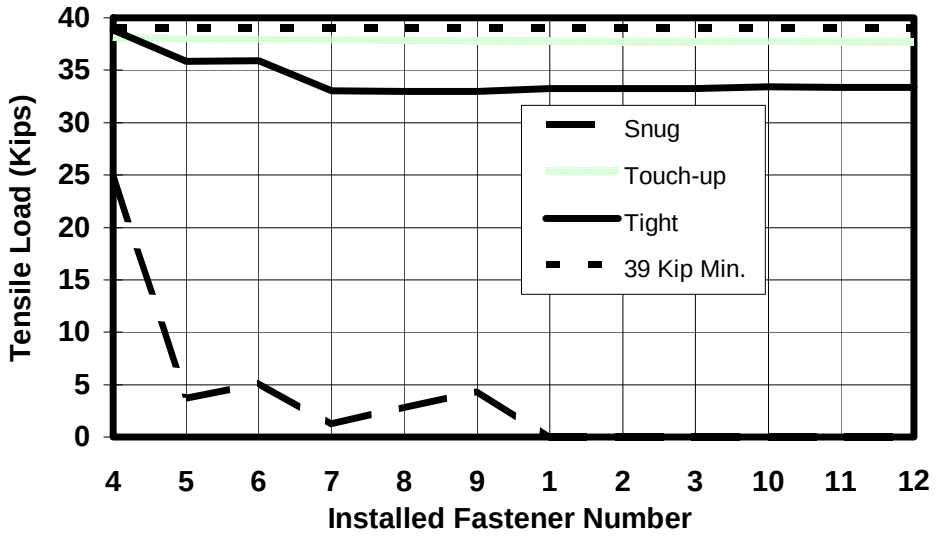


Figure B.118: **Tensile Load History for Fastener #4 - Test CD6CW253.MTO**

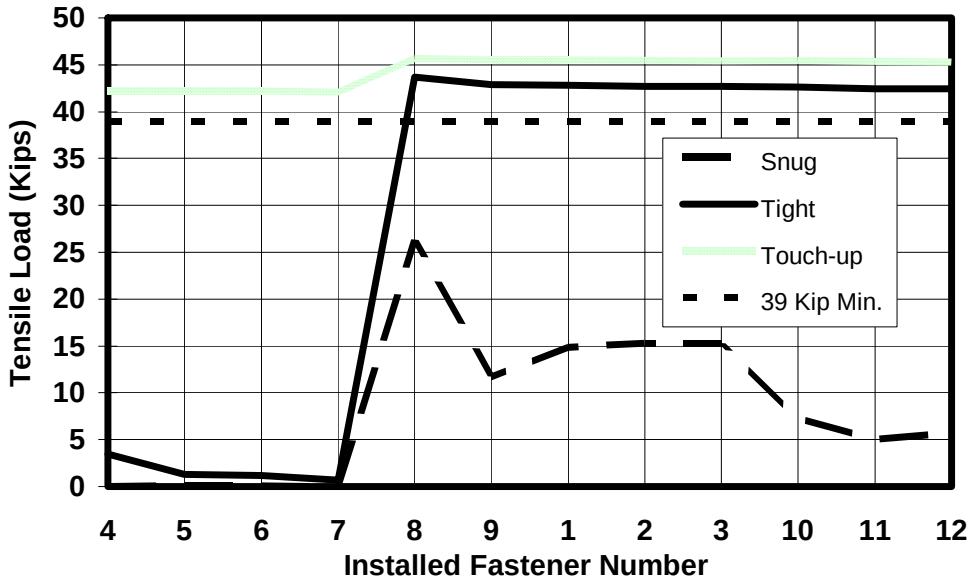


Figure B.119: **Tensile Load History for Fastener #8 - Test CD6CW253.MTO**

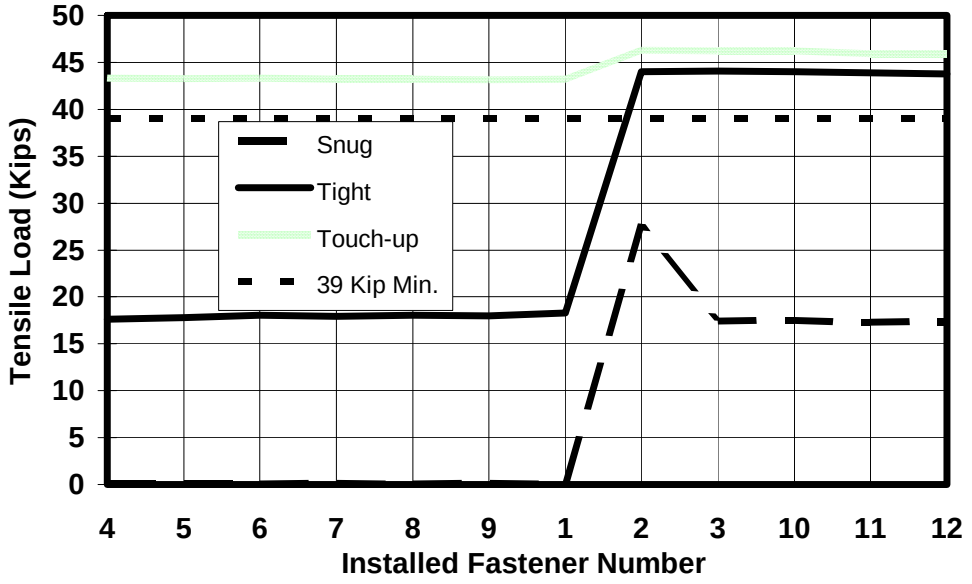


Figure B.120: **Tensile Load History for Fastener #2 - Test CD6CW253.MTO**

Fastener Number

		4	5	6	7	8	9	1	2	3	10	11	12
Snugging Order	4	22.3	0.0	-0.1	0.0	0.1	0.5	0.0	-0.1	-0.1	1.8	0.7	0.5
	5	5.9	26.6	0.0	0.0	0.1	-0.1	0.0	-0.1	0.0	1.9	1.2	0.6
	6	6.5	5.9	27.4	0.0	0.0	0.0	0.1	-0.1	-0.1	1.8	1.1	0.6
	7	-0.1	3.0	22.8	25.8	0.0	0.0	0.1	0.0	0.0	-0.2	-0.1	-0.3
	8	0.5	3.1	15.5	9.2	25.8	0.0	0.0	-0.1	-0.1	-0.2	0.0	-0.3
	9	1.8	4.9	8.0	8.7	9.4	22.9	0.0	-0.1	-0.1	-0.2	-0.1	-0.3
	1	0.0	0.0	-0.1	9.4	10.7	29.2	21.5	0.0	-0.1	-0.1	-0.1	-0.3
	2	-0.1	0.0	-0.1	10.7	10.2	29.0	2.6	28.1	-0.1	0.4	-0.2	-0.4
	3	-0.1	-0.2	0.0	11.4	10.7	27.4	3.2	9.5	26.3	0.9	-0.1	-0.3
	10	-0.1	0.4	0.1	0.8	3.0	20.8	5.7	11.0	27.3	25.7	-0.1	-0.3
	11	-0.1	0.4	0.2	1.8	1.7	11.6	5.8	10.8	28.0	8.0	22.8	-0.3
	12	-0.1	0.5	0.2	3.7	2.6	2.9	5.7	11.1	28.0	7.8	2.4	27.0
Tightening Order	4	43.0	0.2	0.0	-0.2	-0.1	0.7	0.3	5.8	26.6	6.5	1.8	26.6
	5	31.3	43.3	0.0	-0.2	-0.1	-0.2	1.0	5.2	22.6	6.9	1.4	24.8
	6	31.5	35.3	42.0	0.0	-0.1	-0.1	1.3	6.5	19.6	7.2	1.7	22.8
	7	26.1	33.0	41.4	44.3	-0.1	-0.2	2.0	7.0	19.8	2.0	0.6	22.4
	8	26.5	30.8	39.5	37.9	42.6	-0.2	2.2	7.2	20.1	1.2	0.1	17.7
	9	26.7	30.7	33.3	38.0	38.0	41.1	2.4	7.4	20.8	1.3	0.1	10.7
	1	23.7	31.0	33.5	38.1	37.8	40.7	37.9	4.3	19.3	1.3	0.1	10.7
	2	24.1	31.4	33.7	38.0	37.8	40.4	36.8	43.3	15.0	1.4	0.0	10.7
	3	24.1	31.6	33.8	38.0	37.7	40.4	36.9	41.8	44.6	1.3	0.0	10.9
	10	24.6	31.7	33.9	32.2	33.8	40.0	36.8	41.8	44.3	42.8	-0.3	4.9
	11	24.7	31.7	34.1	33.2	32.4	36.7	36.9	41.8	44.2	39.5	42.5	0.1
	12	24.7	31.7	34.1	33.2	33.2	34.7	36.9	41.8	44.2	39.8	38.3	44.5
Touch-up Order	4	42.0	32.5	33.7	32.5	33.2	34.7	36.6	41.7	43.8	39.6	38.2	44.0
	5	41.7	43.2	33.6	32.5	32.9	34.7	36.6	41.7	43.8	39.6	38.1	43.9
	6	41.6	43.0	41.3	32.6	32.9	34.3	36.7	41.8	43.9	39.6	38.1	44.0
	7	41.3	43.0	41.2	42.7	32.8	34.2	36.7	41.8	43.9	39.6	38.2	44.0
	8	41.3	42.9	41.1	42.5	40.7	34.1	36.6	41.7	43.8	39.6	38.1	44.0
	9	41.2	42.8	40.7	42.5	40.5	40.2	36.6	41.8	43.8	39.5	38.2	43.9
	1	41.2	42.7	40.6	42.3	40.5	40.0	37.8	41.8	43.8	39.6	38.1	43.9
	2	41.1	42.7	40.6	42.3	40.4	40.0	37.8	44.1	43.8	39.5	38.1	43.9
	3	41.2	42.7	40.5	42.3	40.4	39.9	37.7	44.1	46.4	39.6	38.1	43.9
	10	41.1	42.6	40.5	42.3	40.3	40.0	37.8	44.1	46.3	42.0	38.1	43.9
	11	41.1	42.7	40.5	42.3	40.3	40.0	37.8	44.1	46.3	42.0	41.0	43.9
	12	41.1	42.7	40.4	42.2	40.3	39.9	37.7	44.0	46.3	41.9	40.9	45.2

Tension in Kips

Average Fastener Tension
(after snugging) = 7.6 Kips
(after tightening) = 36.4 Kips
(after touch-up) = 41.9 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates (6mm gap)
Cal. Wrench Installation (with 25 kip Snug)
Tightened from Middle to Outside

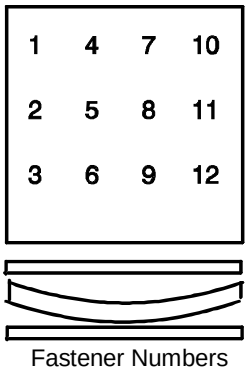


Figure B.121: Fastener Tensions for Test CD6CW254.MTO

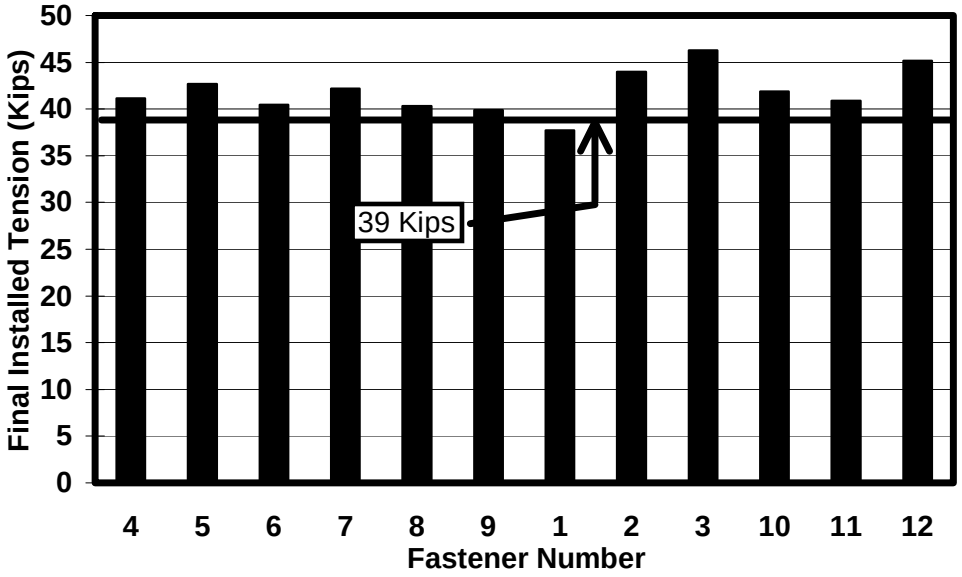


Figure B.122: **Final Installed Tensions for Test**

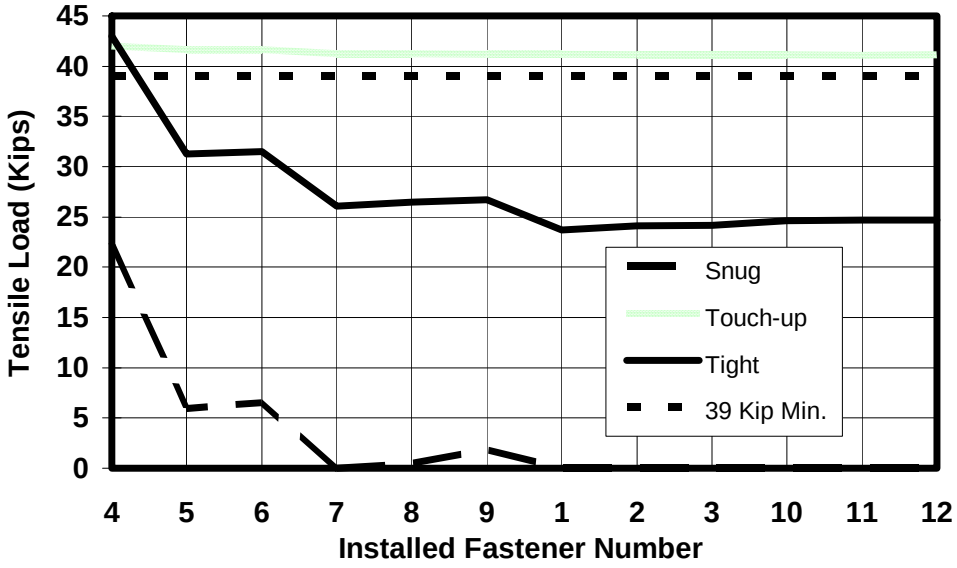


Figure B.123: **Tensile Load History for Fastener #4 - Test CD6CW254.MTO**

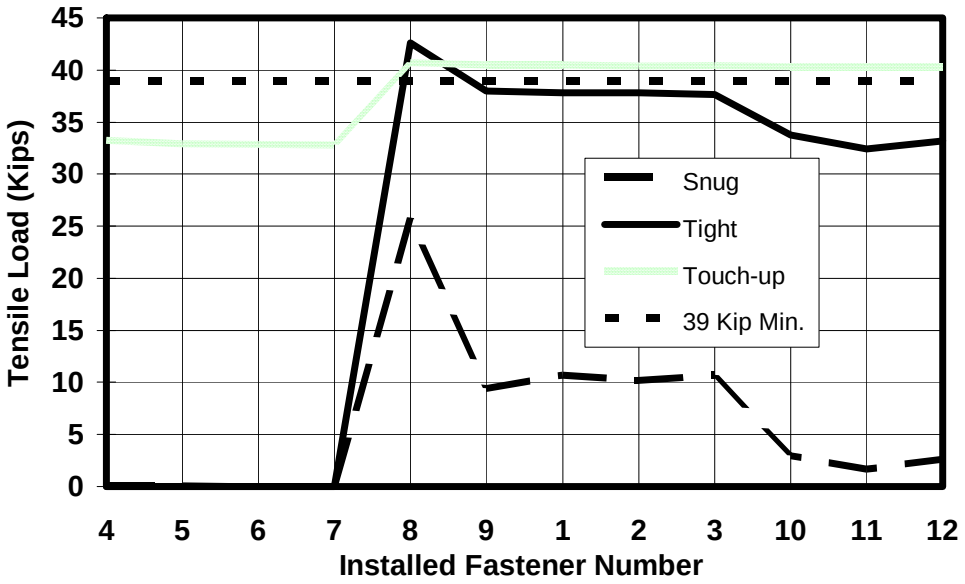


Figure B.124: **Tensile Load History for Fastener #8 - Test CD6CW254.MTO**

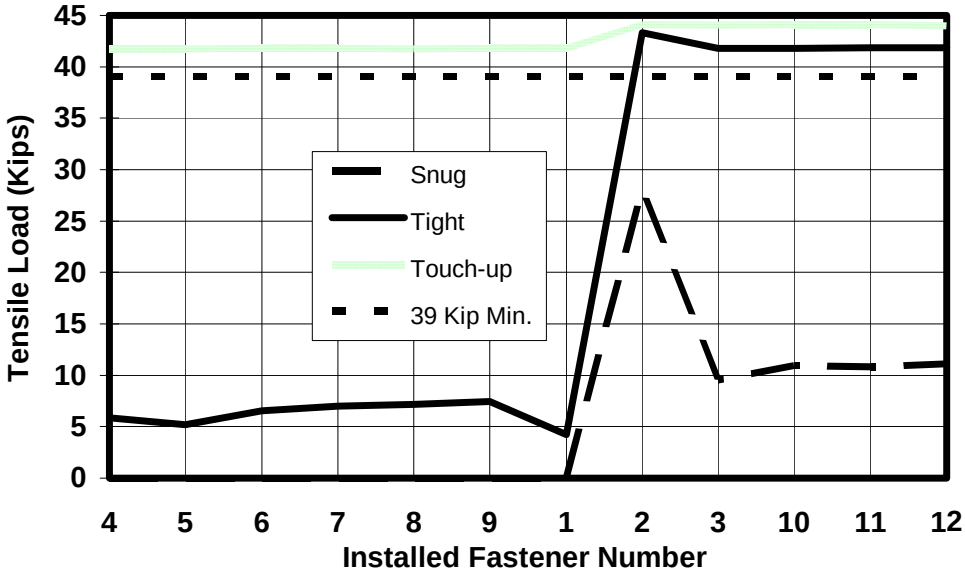


Figure B.125: **Tensile Load History for Fastener #2 - Test CD6CW254.MTO**

APPENDIX C
RESULTS OF CONNECTION TESTS
WITH HUCK C50L FASTENERS

INDEX OF FIGURES

Fastener Number

		a	b	c	d	5	4	6	7	8	9	1	2	3	10	11	12
Snug	a	40.3	0.0	-0.1	0.0	0.0	-0.1	0.3	0.5	-0.1	-0.3	-0.2	-0.2	-0.3	-0.1	-0.1	0.0
	b	38.7	36.4	0.0	0.2	0.0	0.0	0.4	0.5	0.0	-0.3	-0.1	-0.2	-0.3	-0.2	-0.2	-0.1
	c	38.2	35.9	47.8	0.2	0.1	0.1	0.4	0.6	0.1	0.0	-0.1	-0.2	-0.3	-0.1	-0.1	0.0
	d	38.2	35.6	45.6	48.3	0.0	-0.1	0.2	0.6	-0.1	-0.2	-0.2	-0.3	-0.3	-0.1	-0.2	0.0
Installation Order	5	38.3	34.8	44.9	46.6	40.2	0.0	-0.2	0.6	-0.1	-0.2	-0.1	-0.1	-0.2	0.0	-0.1	0.0
	a*	-0.2	34.8	44.6	46.6	40.2	-0.1	-0.1	0.6	0.0	-0.1	0.0	-0.1	-0.2	-0.1	-0.2	0.0
	4	-0.2	34.9	44.8	46.6	40.0	40.9	0.0	0.8	0.1	-0.1	0.0	-0.1	-0.3	-0.1	-0.2	-0.1
	b*	-0.5	0.1	44.7	46.3	40.2	40.1	0.0	0.8	0.0	-0.2	0.0	-0.2	-0.3	-0.1	-0.2	0.1
	6	-0.3	-0.1	44.7	46.2	39.6	40.1	41.7	0.8	0.0	-0.2	0.0	-0.1	-0.4	-0.1	-0.2	0.0
	c*	-0.3	0.0	-0.4	46.4	39.6	39.8	40.9	0.9	0.0	-0.2	-0.1	-0.2	-0.4	-0.2	-0.3	0.0
	7	-0.2	0.0	-0.4	46.1	39.7	40.0	41.1	40.2	0.1	-0.1	0.0	0.0	-0.2	-0.1	-0.1	0.1
	8	-0.4	0.1	-0.2	46.0	39.7	40.0	41.2	39.3	38.5	0.0	0.0	-0.1	-0.3	-0.1	-0.2	0.0
	d*	-0.1	0.2	-0.2	-0.4	39.5	39.8	40.9	39.2	38.5	-0.2	-0.1	-0.2	-0.3	0.0	-0.1	0.1
	9	-0.2	0.0	-0.4	-0.7	39.4	39.7	40.9	39.0	37.5	39.8	-0.1	-0.2	-0.3	-0.1	-0.2	0.2
	1	-0.2	0.1	-0.3	-0.8	39.4	40.2	40.6	39.0	37.5	39.1	39.8	-0.2	-0.3	0.0	-0.1	0.2
	2	-0.3	0.1	-0.3	-0.7	39.8	40.3	40.6	39.1	37.6	39.2	39.9	40.5	-0.3	0.0	-0.1	0.2
	3	-0.4	0.1	-0.3	-0.6	39.8	40.2	40.9	39.0	37.5	39.0	39.7	40.2	40.9	-0.1	-0.2	0.1
	10	-0.3	0.1	-0.3	-0.8	39.7	40.1	40.8	39.0	37.4	39.0	39.6	40.1	40.3	38.2	-0.2	0.1
	11	-0.3	0.0	-0.3	-0.7	39.7	40.2	41.0	39.0	37.8	39.1	39.7	40.2	40.1	38.2	40.7	0.2
	12	-0.2	0.0	-0.4	-0.9	39.6	40.1	40.7	38.8	37.6	39.4	39.5	40.0	40.0	37.9	40.7	40.2

Tension in Kips

Average Fastener Tension
(after snugging with 4 conventional bolts) = 41.9 Kips
(after installation) = 39.5 Kips

28 Grip Huck C50L Fasteners
2" Grip
Deformed Plates (3mm gap)
One Pass Intallation
Installed from Middle to Outside

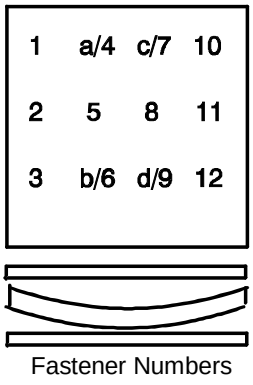


Figure C.1: Fastener Tensions for Test HD3CS412.MTO

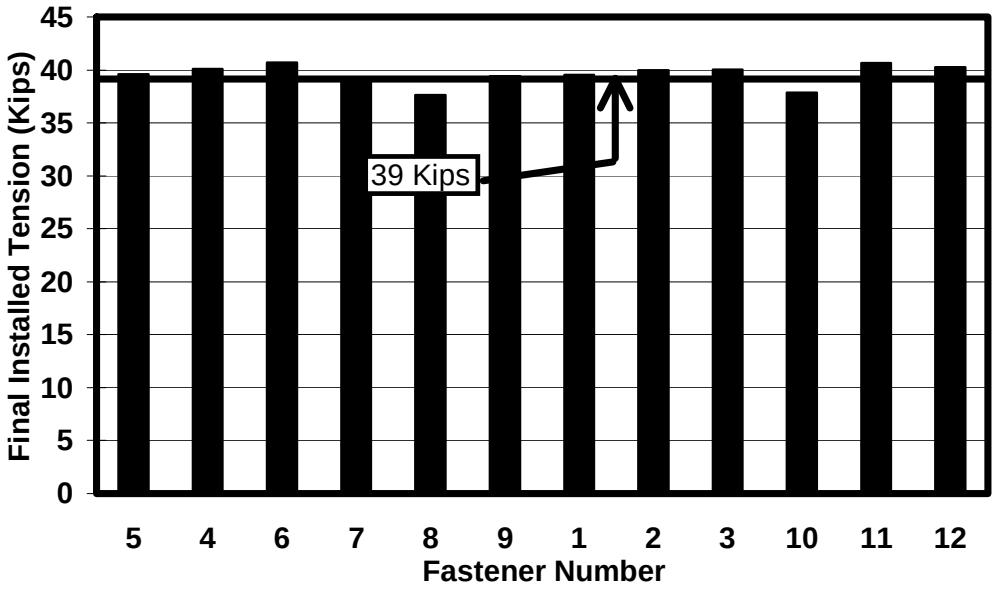


Figure C.2: **Final Installed Tensions for Test HD3CS412.MTO**

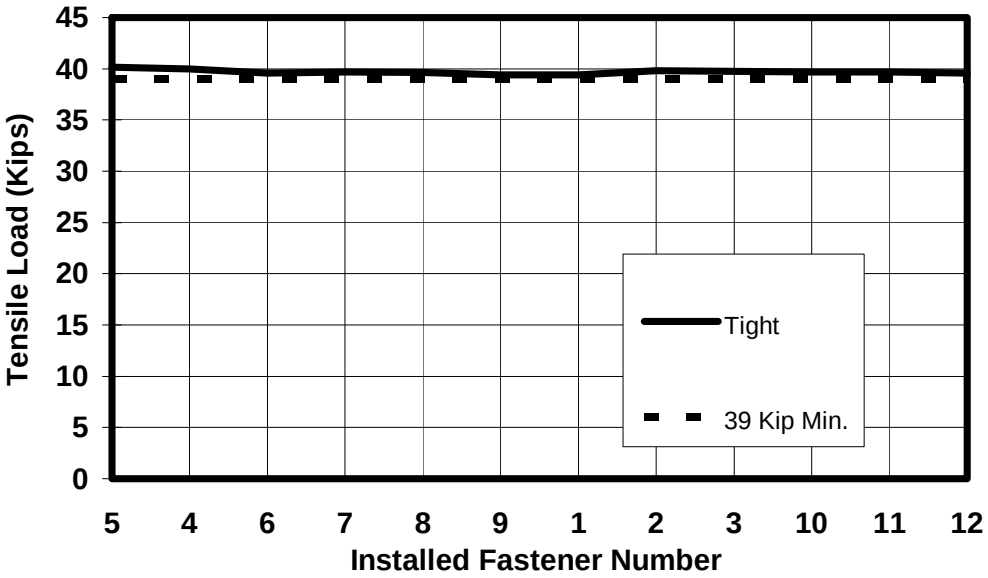


Figure C.3: **Tensile Load History for Fastener #5 - Test HD3CS412.MTO**

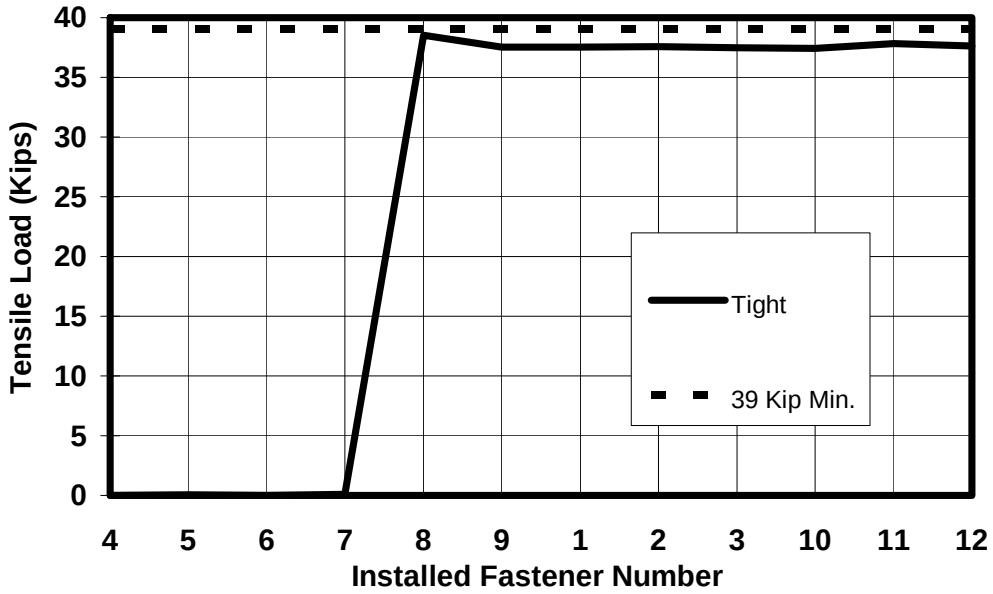


Figure C.4: **Tensile Load History for Fastener #8 - Test HD3CS412.MTO**

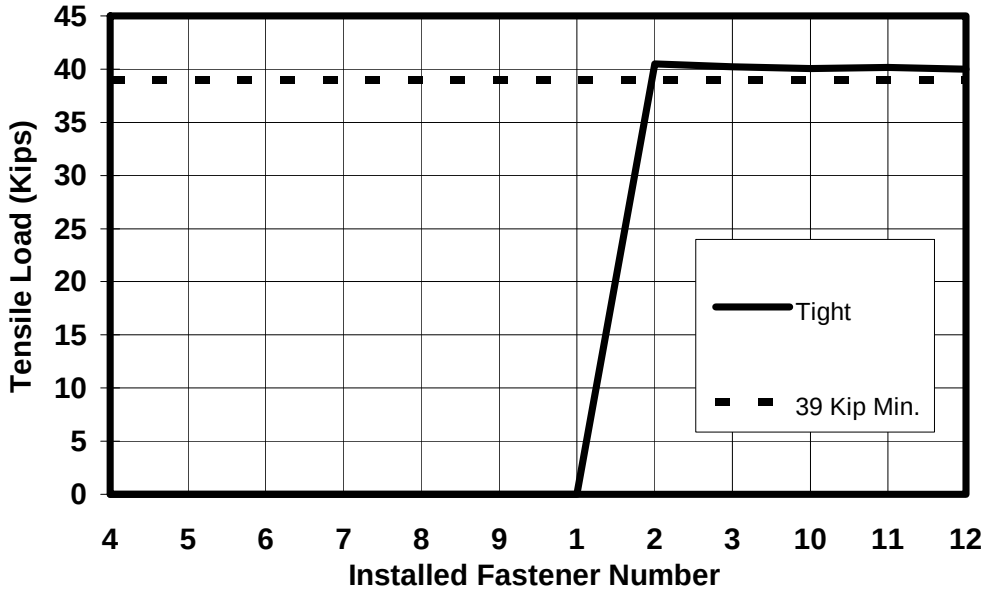


Figure C.5: **Tensile Load History for Fastener #2 - Test HD3CS412.MTO**

Fastener Number

		a	b	c	d	5	4	6	7	8	9	1	2	3	10	11	12
Snug	a	39.1	0.1	0.0	0.1	0.0	0.0	-0.1	0.1	-0.1	0.0	0.0	0.1	-0.1	0.1	0.1	0.1
	b	28.7	50.2	0.1	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0
	c	28.3	48.5	52.5	0.1	0.0	0.0	-0.1	0.0	-0.1	0.0	0.0	0.1	0.0	0.1	0.1	0.1
	d	29.5	49.0	45.7	39.2	0.0	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	a	36.3	48.6	45.5	38.7	0.0	0.0	-0.1	-0.1	0.0	0.1	0.0	0.0	-0.2	0.0	0.1	0.0
Installation Order	5	32.8	45.7	45.3	38.2	39.4	0.0	-0.1	-0.1	0.0	0.1	0.0	0.1	B.G.	0.0	0.1	0.0
	a*	0.1	45.9	44.9	38.0	41.4	0.1	0.1	0.0	0.1	0.2	0.1	0.1	B.G.	0.2	0.2	0.0
	4	0.1	45.8	45.0	38.2	37.1	40.1	0.1	0.2	0.1	0.1	0.1	0.2	B.G.	0.2	0.2	0.0
	b*	0.0	0.2	44.6	37.3	42.2	39.9	-0.1	0.2	-0.1	0.0	0.1	0.2	B.G.	0.3	0.2	0.0
	6	0.1	0.3	45.1	37.7	36.5	39.7	40.6	0.3	0.1	0.1	0.1	0.2	B.G.	0.3	0.2	0.0
	c*	0.1	0.2	0.3	40.6	35.6	39.5	39.4	0.4	-0.1	0.1	0.1	0.2	B.G.	0.3	0.3	0.1
	7	0.1	0.3	0.3	37.2	36.8	39.2	40.1	42.8	0.0	0.1	0.1	0.3	B.G.	0.3	0.4	0.1
	8	0.1	0.3	0.4	33.8	36.4	39.3	40.7	39.5	40.6	0.1	0.1	0.2	B.G.	0.3	0.3	0.1
	d*	0.1	0.3	0.4	0.2	35.8	39.3	40.0	39.8	41.7	0.1	0.1	0.2	B.G.	0.3	0.3	0.0
	9	0.1	0.1	0.2	0.0	36.4	39.3	40.1	39.6	38.0	38.8	0.1	0.2	B.G.	0.3	0.3	0.1
	1	0.1	0.2	0.3	0.1	34.8	38.5	38.3	39.7	38.2	38.9	40.9	0.3	B.G.	0.3	0.4	0.1
	2	0.1	0.3	0.3	0.2	34.7	38.8	35.7	39.8	38.1	39.0	40.2	39.8	B.G.	0.3	0.4	0.0
	3	0.1	0.7	0.3	0.2	35.0	38.7	33.8	39.7	38.1	39.3	40.1	39.8	B.G.	0.3	0.3	0.0
	10	0.1	0.6	0.2	0.0	34.9	38.7	33.9	37.2	36.7	37.6	40.1	39.6	B.G.	36.3	0.4	0.1
	11	0.1	0.7	0.4	0.1	35.0	38.7	33.9	37.4	36.4	35.4	40.1	39.6	B.G.	36.1	41.2	0.1
	12	0.2	0.7	0.4	0.2	35.0	38.7	33.9	37.2	36.4	34.2	40.1	39.5	B.G.	35.6	40.8	40.1

Tension in Kips

Average Fastener Tension
(after snugging with 4 conventional bolts) = 42.3 Kips
(after installation) = 37.4 Kips

44 Grip Huck C50L Fasteners
3" Grip
Deformed Plates (3mm gap)
One Pass Intallation
Installed from Middle to Outside

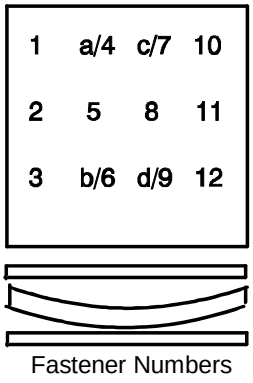


Figure C.6: Fastener Tensions for Test HD3CS413.MTO

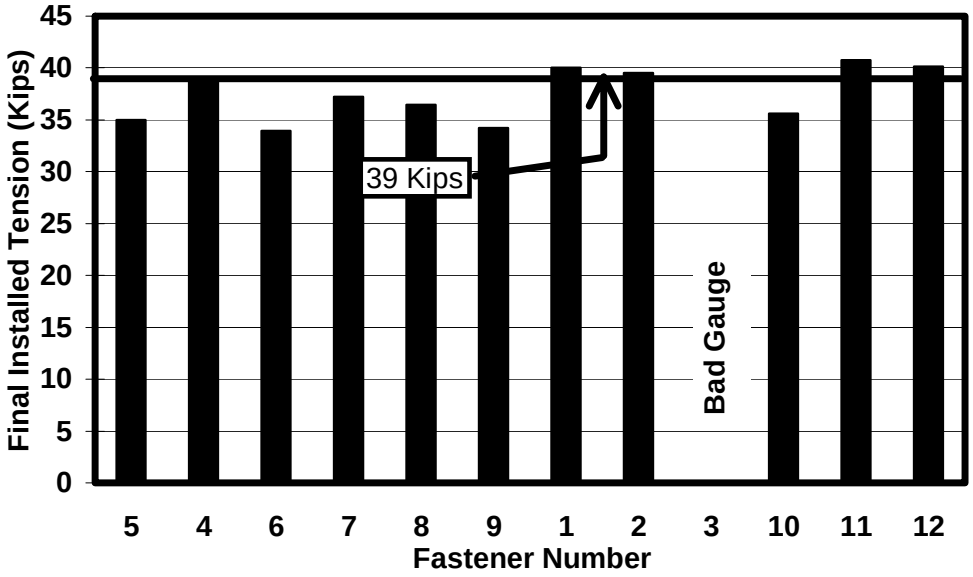


Figure C.7: Final Installed Tensions for Test HD3CS413.MTO

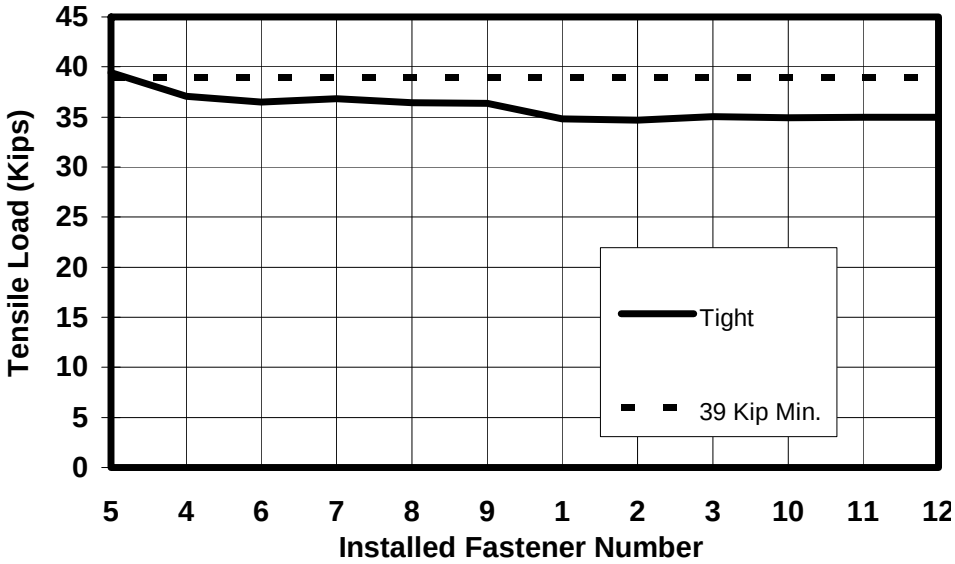


Figure C.8: Tensile Load History for Fastener #5 - Test HD3Cs413.MTO

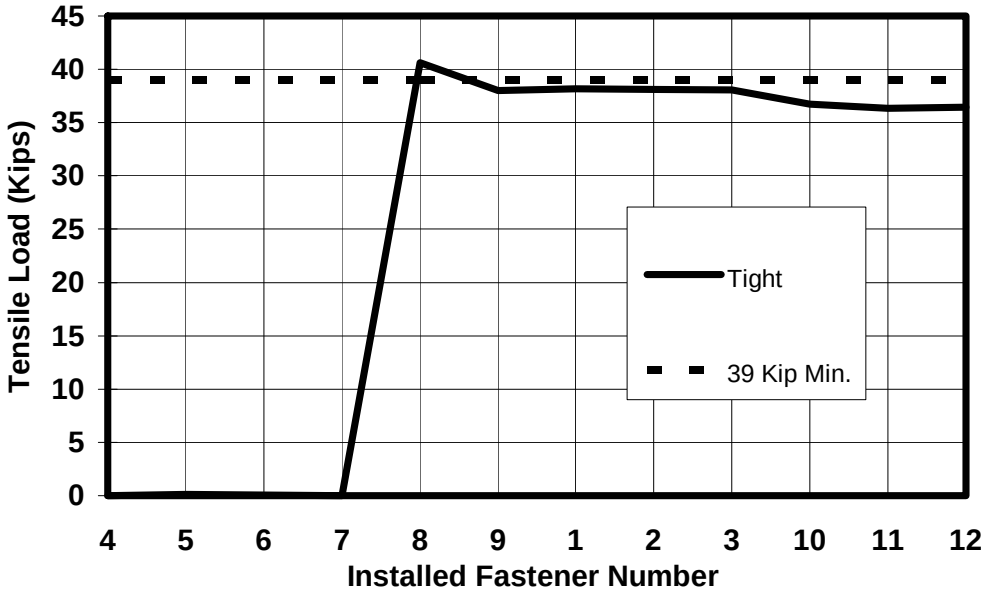


Figure C.9: **Tensile Load History for Fastener #8 - Test HD3CS413.MTO**

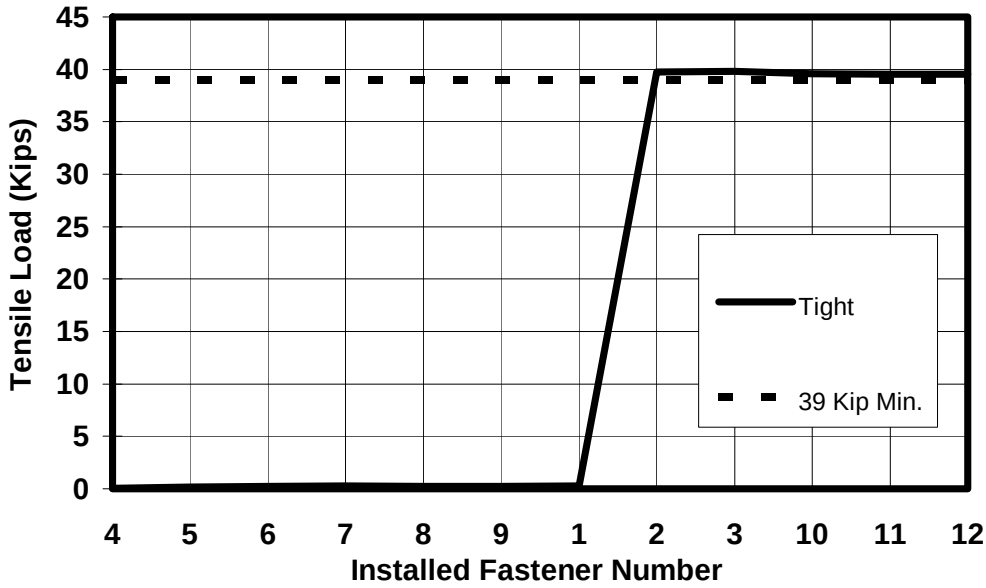


Figure C.10: **Tensile Load History for Fastener #2 - Test HD3CS413.MTO**

Fastener Number

		a	b	c	d	5	4	6	7	8	9	1	2	3	10	11	12
Snug	a	38.1	-0.1	-0.1	-0.2	-0.1	-0.1	-0.3	-0.1	-0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0
	b	22.0	46.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.0	-0.1	0.0
	c	20.3	44.6	38.7	-0.2	-0.2	-0.2	-0.2	0.0	0.0	0.0	-0.1	-0.1	0.0	-0.1	-0.2	0.0
	d	26.0	46.5	30.0	45.8	-0.2	-0.2	-0.3	0.1	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	-0.1
	a	39.2	45.5	30.2	45.6	-0.1	-0.1	-0.3	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
	c	39.0	45.7	39.0	44.9	-0.2	-0.2	-0.1	0.1	0.1	0.0	0.0	-0.1	0.0	0.0	-0.1	0.1
Installation Order	5	31.4	39.9	38.9	45.9	41.4	0.0	-0.2	0.1	0.0	0.0	-0.1	-0.1	0.0	0.0	-0.1	0.1
	a*	-0.1	40.9	36.9	44.3	43.9	-0.2	-0.2	0.2	-0.1	-0.1	-0.1	-0.2	-0.1	-0.2	-0.2	0.0
	4	-0.1	39.5	38.6	45.9	37.2	41.2	-0.2	0.3	-0.1	-0.1	-0.1	-0.1	0.0	0.0	-0.1	0.1
	b*	-0.1	0.7	37.2	44.5	42.4	41.9	-0.1	0.3	0.0	0.1	0.0	-0.1	0.0	-0.1	-0.1	0.1
	6	-0.1	0.6	38.6	45.2	36.7	40.4	44.7	0.2	0.0	0.0	-0.1	-0.1	0.0	0.0	-0.1	0.1
	c*	-0.2	0.7	1.0	48.9	34.1	39.1	41.1	0.3	0.0	0.1	-0.1	-0.1	0.0	0.0	-0.1	0.7
	7	-0.1	0.8	1.1	44.3	36.9	40.0	43.7	42.5	0.0	0.1	-0.1	0.0	0.1	0.0	-0.1	0.8
	8	-0.1	0.7	0.9	38.0	37.1	41.1	45.2	36.0	42.6	0.0	-0.2	-0.1	0.0	-0.1	-0.1	0.7
	d*	-0.2	0.8	0.9	-0.3	34.4	39.8	44.4	37.2	46.5	-0.1	-0.2	-0.2	-0.1	-0.2	-0.3	0.5
	9	-0.2	0.7	1.0	-0.1	37.2	41.0	44.3	35.9	38.3	40.6	-0.1	-0.1	0.0	-0.1	-0.1	0.7
	1	-0.2	0.8	1.0	0.0	31.9	36.2	40.8	36.3	38.6	40.8	41.9	-0.1	0.0	-0.1	-0.3	0.5
	2	-0.2	0.8	1.1	0.0	30.6	36.9	36.9	36.2	38.7	41.2	38.3	40.5	0.0	-0.1	-0.2	0.5
	3	-0.3	0.7	0.9	-0.2	31.1	36.8	36.8	33.1	35.6	38.5	38.2	36.3	38.2	-0.1	-0.3	0.5
	10	-0.2	0.7	0.8	-0.1	31.3	37.3	37.1	29.7	32.2	36.4	38.3	36.4	38.3	42.1	-0.2	0.6
	11	-0.3	0.7	0.8	-0.2	31.3	37.2	37.4	30.3	30.9	32.7	38.2	36.3	38.2	40.7	41.2	0.4
	12	-0.2	0.7	0.9	0.0	31.2	37.2	37.7	30.2	31.5	32.0	38.2	36.3	38.2	40.7	38.5	42.4

Tension in Kips

Average Fastener Tension
(after snugging with 4 conventional bolts) = 42.1 Kips
(after installation) = 36.2 Kips

60 Grip Huck C50L Fasteners
4" Grip
Deformed Plates (3mm gap)
One Pass Intallation
Installed from Middle to Outside

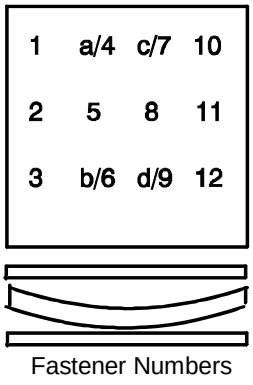


Figure C.11: Fastener Tensions for Test HD3CS41.MTO

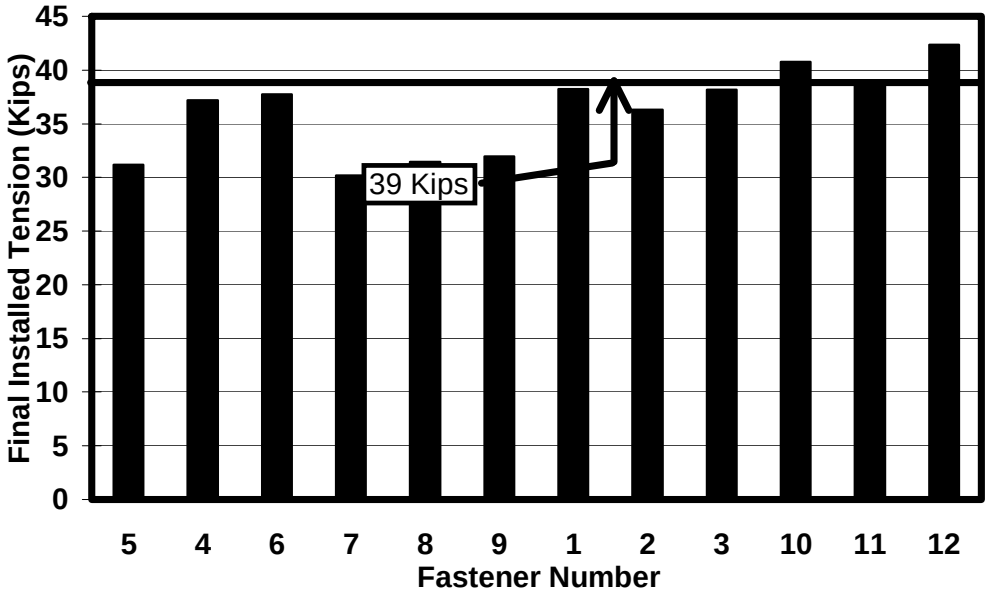


Figure C.12: **Final Installed Tensions for Test HD3CS414.MTO**

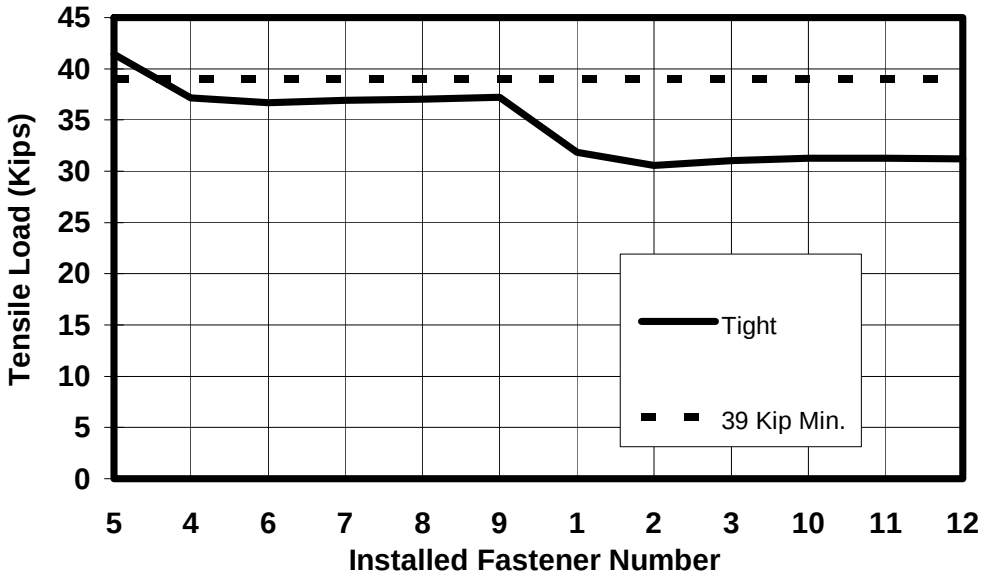


Figure C.13: **Tensile Load History for Fastener #5 - Test HD3CS414.MTO**

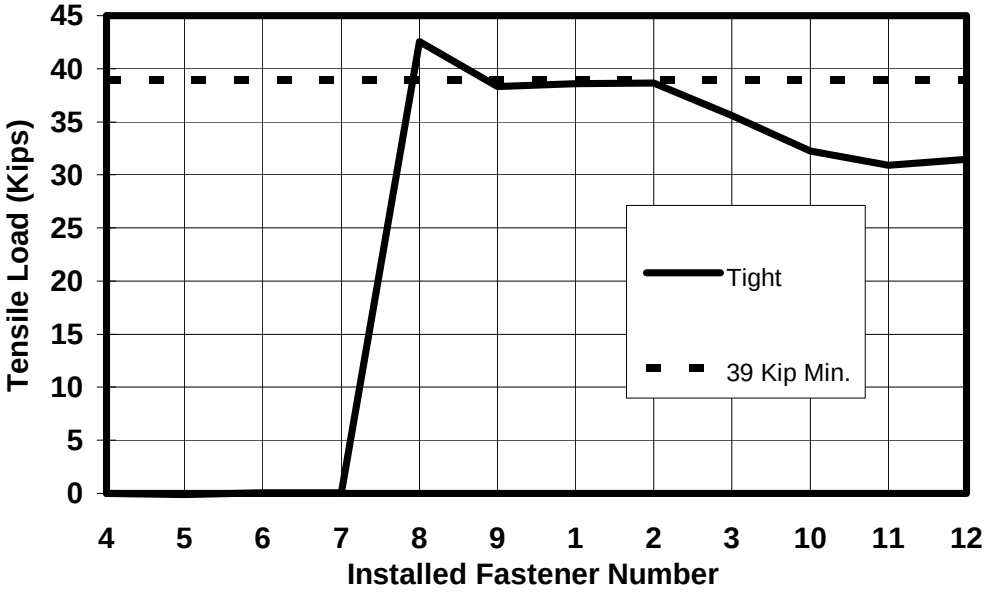


Figure C.14: **Tensile Load History for Fastener #8 - Test HD3CS414.MTO**

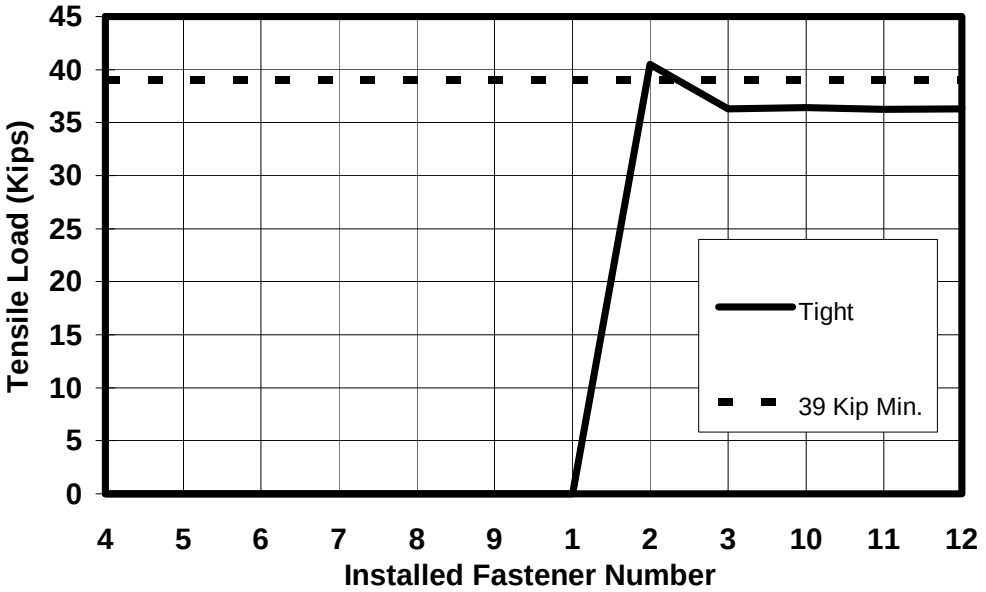


Figure C.15: **Tensile Load History for Fastener #2 - Test HD3CS414.MTO**

Fastener Number

Installation	4	5	6	7	8	9	1	2	3	10	11	12
4	42.1	0.2	0.1	0.0	-0.1	0.0	0.1	0.2	0.2	0.1	0.4	0.1
5	36.3	39.6	0.1	0.0	0.0	0.0	0.3	0.1	0.1	0.0	0.9	0.0
6	36.4	36.9	44.8	0.0	0.2	0.0	0.2	0.0	0.1	0.0	0.6	0.2
7	35.4	35.0	43.2	36.4	0.0	0.0	0.3	0.1	0.1	0.1	0.3	0.2
8	33.6	34.5	42.9	26.0	42.0	0.0	0.5	0.1	0.1	0.1	0.6	0.2
9	33.7	34.5	42.1	25.2	36.0	39.4	0.2	0.0	0.0	0.0	0.7	0.2
1	33.6	33.9	41.3	25.3	36.0	38.6	40.0	0.1	0.1	0.0	0.6	0.3
2	34.0	34.1	39.9	25.2	36.1	38.6	39.7	38.9	0.2	0.1	0.7	0.3
3	34.5	34.2	39.7	25.2	36.1	38.5	39.4	38.7	40.7	0.1	0.9	0.4
10	34.4	34.1	39.7	22.5	34.8	38.0	39.4	38.6	40.0	38.3	0.8	0.4
11	34.8	34.0	39.5	22.4	34.4	36.9	39.2	38.6	40.0	38.8	38.0	0.3
12	34.7	34.0	39.5	22.4	34.5	36.4	39.2	38.5	39.8	38.5	38.1	43.6

Tension in Kips

Average Fastener Tension
(after Installation) = 36.6 Kips

28 Grip Huck Fasteners
2" Grip
Deformed Plates (6mm gap)
One Pass Installation
Tightened from Middle to Outside

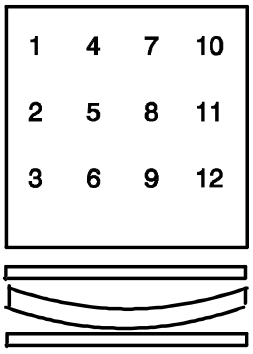


Figure C.16: Fastener Tensions for Test HD6NS--2.MTO

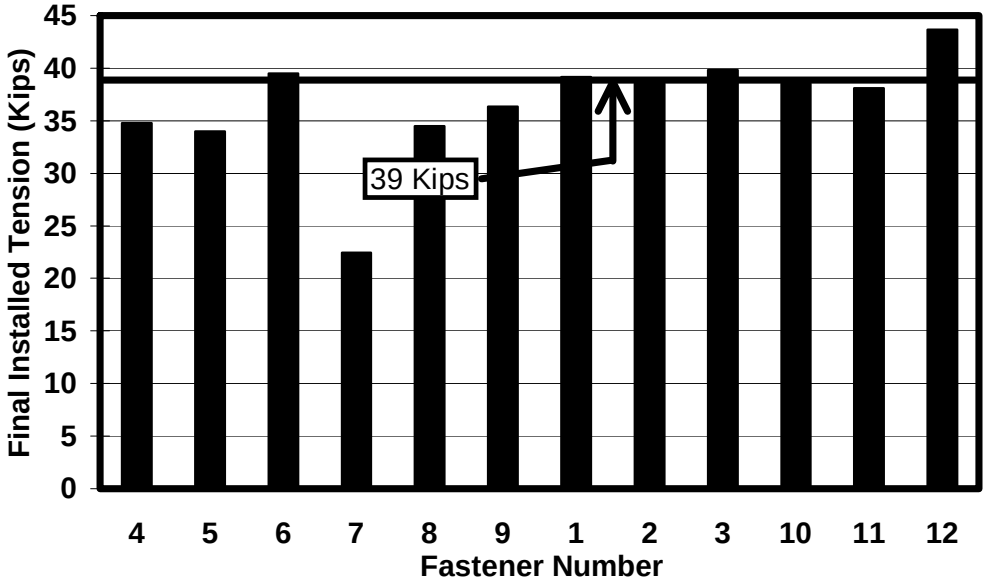


Figure C.17: **Final Installed Tensions for Test HD6NS--2.MTO**

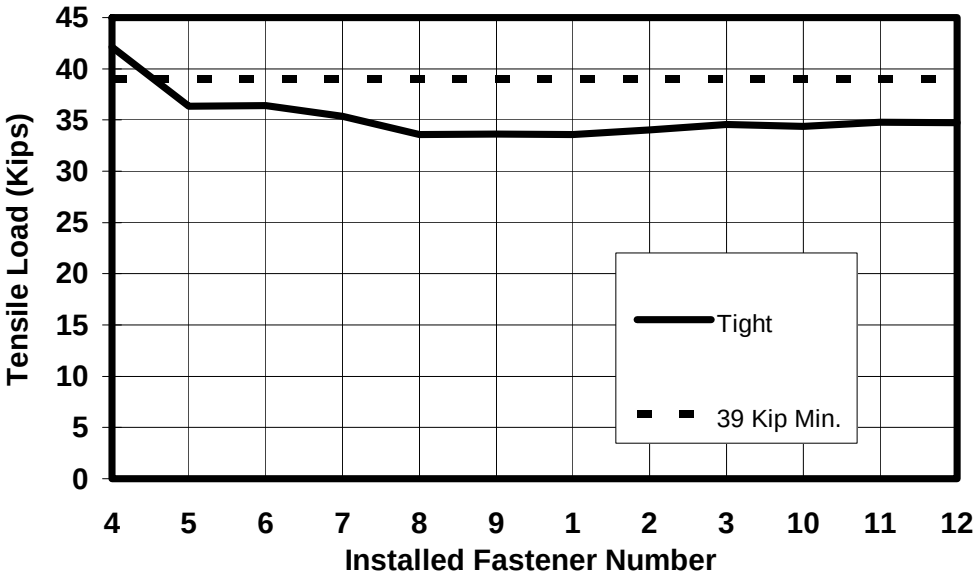


Figure C.18: **Tensile Load History for Fastener #4 - Test HD6NS--2.MTO**

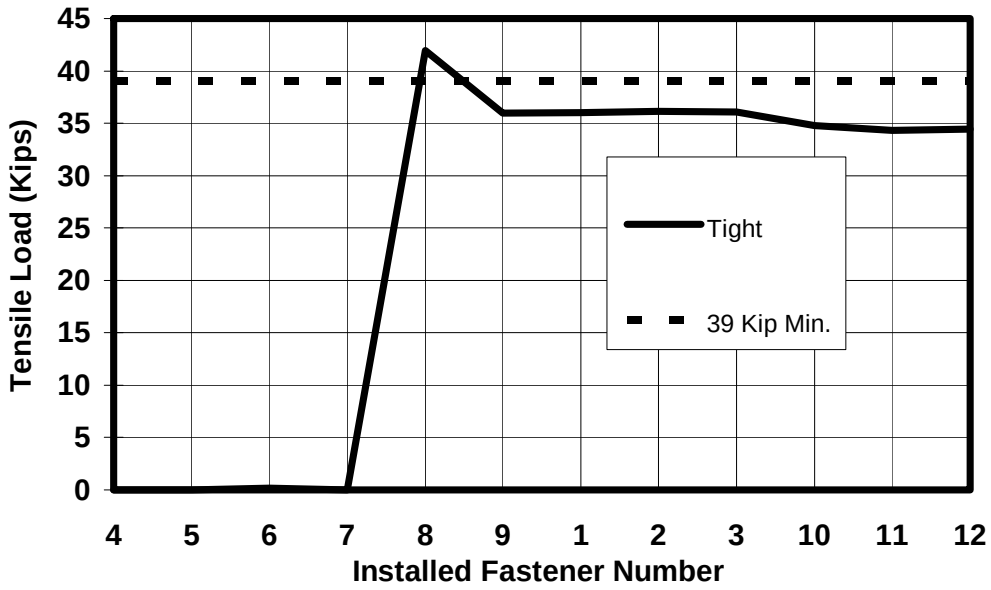


Figure C.19: **Tensile Load History for Fastener #8 - Test HD6NS--2.MTO**

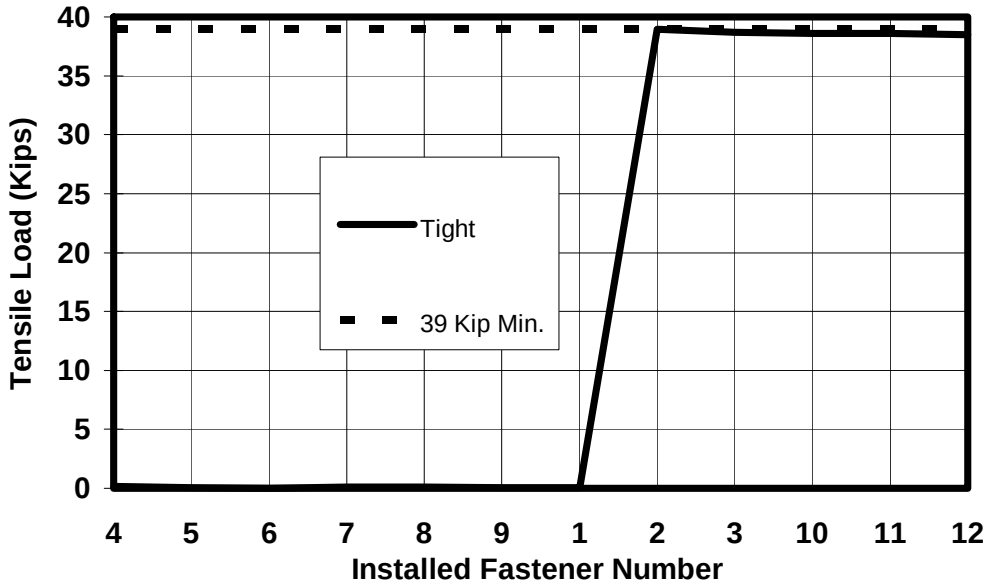


Figure C.20: **Tensile Load History for Fastener #2 - Test HD6NS--2.MTO**

BIBLIOGRAPHY

1. "Load and Resistance Factor Design Specification for Structural Joints Using ASTM A325 or A490 Bolts", Research Council on Structural Connections of the Engineering Foundation, June 1988.

2. Kulak, G.L., Fisher, J.W., and Struik, J.A., Guide to Design Criteria for Bolted and Riveted Joints, Second Edition, John Wiley and Sons, New York, 1987.

3. Kulak, G.L., and Obaia, K.H., "A Field Study of Fastener Tension in High-Strength Bolts", *Structural Engineering Report No. 177*, Department of Civil Engineering, University of Toronto, April 1992.

4. Notch, J.S., "A Field Problem with Preload of Large A490 Bolts", *The Structural Engineer*, Volume 64A, No. 4, April 1986.

5. Foreman, R.T., and Rumpf, J.L., "Static Tension Tests of Compact Bolted Joints",*Transactions of the American Society of Civil Engineers*, Volume 126-Part 2, 1961, pp. 228-254.

6. Birkemoe, Peter C., "Installation Tension of High-Strength Bolts in Connections with Out-of-Flat Plates", *IABSE International Colloquium*, Bolted and Special Structural Joints, USSR, Moscow, May 1989.

BIBLIOGRAPHY

1. "Load and Resistance Factor Design Specification for Structural Joints Using ASTM A325 or A490 Bolts", Research Council on Structural Connections of the Engineering Foundation, June 1988.

2. Kulak, G.L., Fisher, J.W., and Struik, J.A., Guide to Design Criteria for Bolted and Riveted Joints, Second Edition, John Wiley and Sons, New York, 1987.

3. Kulak, G.L., and Obaia, K.H., "A Field Study of Fastener Tension in High-Strength Bolts", *Structural Engineering Report No. 177*, Department of Civil Engineering, University of Toronto, April 1992.

4. Notch, J.S., "A Field Problem with Preload of Large A490 Bolts", *The Structural Engineer*, Volume 64A, No. 4, April 1986.

5. Foreman, R.T., and Rumpf, J.L., "Static Tension Tests of Compact Bolted Joints", *Transactions of the American Society of Civil Engineers*, Volume 126-Part 2, 1961, pp. 228-254.

6. Birkemoe, Peter C., "Installation Tension of High-Strength Bolts in Connections with Out-of-Flat Plates", *IABSE International Colloquium*, Bolted and Special Structural Joints, USSR, Moscow, May 1989.