TESTS ON THE INSTALLED TENSIONS OF LOCK-PIN AND COLLAR FASTENERS IN LAP SPLICE JOINTS

by

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ABSTRACT

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In slip-critical bolted joints, adequate values of final installed fastener tensions are essential to ensure proper behavior of the joint. Each fastener must develop a certain minimum value of tension upon final installation. These minimum tensions are stipulated by the Research Council on Structural Connections.

This report describes the development of a method for the measurement of fastener tension using electrical resistance strain gauges. Included herein are the results of specific tests designed to determine the validity of the method as applied to different fasteners under different installation conditions.

The installed tensions of lock-pin and collar fasteners in multi-plate lap splices are investigated at both the snug tight and full tight levels. These are compared to the corresponding tensions exhibited by conventional nut and bolt fasteners in similar installations. The tensions of both fastener types are compared to the minimum value required. The effects of several variables on fastener tension, including plate out-of-flatness, plate thickness, type of fastener, method of fastener installation, and degree of fastener snugging are studied. A testing program which utilizes different combinations of these variables is described. The results of these fastener tests, as well as a discussion of their results, is contained in this report.

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

This report summarizes a study of fastener tensions developed in steel lap splice connections constructed with lock-pin and collar fasteners. The final installed tensions in the fasteners of a slip-critical structural connection are of the utmost importance to the integrity of the connection. Tensile loads in the fasteners induce frictional forces between the connected plates which are relied upon to resist slip. Slip-critical connections of this type are often found in bridges and in seismic resistant structures where dynamic loadings are expected.

Fastener tension, or preload, depends on several variables. Included among these are the method of fastener installation, sequence of the installation of the fasteners, and out-of-flatness (warping) of the connected plates. In connections with large numbers of fasteners the effects and interactions of these variables are not well understood.

In a multiple fastener connection, the tension in an individual fastener may be affected by the subsequent installation of surrounding fasteners. As neighboring fasteners are tightened, the plies of the connection are pulled into firmer contact, thus relieving a portion of the tension in the previously installed fastener. In connections with multiple fasteners and out-of-flat plates, the plate distortion tends to increase preload loss in the connecting fasteners.

The "Specification for Structural Joints Using ASTM A325 or A490 Bolts" published by the Research Council on Structural Connections of the Engineering Foundation (RCSC) addresses the issue of fastener tension in slip-critical bolted connections. This document will hereafter be referred to as the *Bolt Specification*. The *Bolt Specification* specifies both minimum required fastener tensions and installation procedures intended to achieve them. Minimum installed tension is defined as 70% of the minimum tensile strength of the fastener, rounded to the nearest kip. There are several procedures for installation of structural fasteners that are approved by the RCSC. These methods are discussed below.

1.2 CURRENT METHODS OF FASTENER INSTALLATION

There are currently four methods approved by the RCSC for installation of fasteners in slip-critical connections [1]. Three of these procedures are applicable to conventional nut and bolt fastener assemblies. The fourth method of installation deals with fasteners that have built-in features such as twist-off or fracture of certain segments of the fastener to ensure adequate tension. Following is a brief description of these methods.

The first, referred to as the *calibrated wrench method*, utilizes a calibrated torque-tension relationship for the fastener. Using a device capable of indicating fastener tension (a Skidmore-Wilhelm bolt tension indicator is commonly used), the torque required to achieve at least 5 percent in excess of the minimum required tension is determined. RCSC requires that a sample of 3 fasteners be used to establish this required torque. A hardened washer is required during the calibration procedure and in the actual connection, under the element turned during tightening (typically the nut). A torque-tension relationship must be established for each fastener, nut, and washer combination used.

During installation of fasteners in the actual connection, RCSC requires the connection be first brought to a snug tight condition. Snug tight is defined as "the tightness that exists when the plies of the joint are in firm contact". The *Bolt Specification* indicates that snug tight "may be usually be attained by a few impacts of an impact wrench or the full effort of a man using an ordinary spud wrench". Next, a torque which will produce a fastener tension that is 5% above the minimum required tension is applied to each fastener. This is known as a "tightening" pass and is accomplished by using a manual torque wrench which is set to the appropriate torque value or an adjustable air powered impact wrench set to cut-off at the appropriate torque value. According to RCSC, the pattern for fastener snugging and tightening begins with those connectors in the most rigid part of the connection and proceeds to the free edges of the plates. Finally, RCSC notes that more than a single cycle of tightening may be required to assure that all fasteners have achieved their minimum required tension. Additional cycles of tightening are sometimes referred to as "touch-up" passes.

The second procedure, referred to as the *turn-of-nut* method, begins with a snugging pass identical to that used in the calibrated wrench method. After snugging, all nuts are turned an additional fraction of a turn relative to the bolt. The specified amount of rotation is depends on the length of the bolt and is listed in the RCSC *Bolt Specification*. Again, tightening and snugging proceed from the most rigid part of the connection to the free edges. A nut and bolt properly installed by this method will almost always exhibit yielding in the threads of the bolt between the nut and the gripped material [2].

Direct tension indicators are a third method of monitoring installed fastener tensions. An example of such a device is the load indicating washer in which pre-formed extrusions on the face of the washer are compressed by the bolt head and the material in the grip. The gap between the surface of the material and the face of the washer serves as an indication of the tension in the bolt [2]. When direct tension indicators are used the *Bolt Specification* requires that all fasteners be snugged prior to the commencement of tightening operations.

Lastly, fasteners may be installed that rely on certain design features that ensure adequate preload. These *Alternate Design Bolts* typically utilize spline tails that shear off under a specified torque or break-necks that fracture at a given tensile load. These load control mechanisms are usually irreversible, and tightening past the point where the mechanism is activated is usually difficult or impossible. Typically, these connectors require special installation tools to utilize their load control features. As with the three previously mentioned techniques, the *Bolt Specification* requires that these fasteners must all be snugged prior to final tightening.

Before using any of the four methods, the *Bolt Specification* dictates that a sample of the fasteners to be installed must be checked to ensure the adequacy of the installation technique to provide the minimum specified tension. The sample should consist of not less than three fasteners of each diameter, length, and grade to be installed. In the field, tensile loads are most easily verified through the use of a Skidmore-Wilhelm bolt tension indicator.

Although the RCSC *Bolt Specification* outlines procedures for correct installation of structural fasteners as described above, questions exist pertaining to the adequacy of these specifications to ensure adequate fastener preloads. Of particular interest is the RCSC definition of snug-tight (a few impacts of an impact wrench or the full effort of a man using an ordinary spud wrench) [1]. The intent of the snug tight provision is to minimize final fastener preload loss due to plate deformation in multiple fastener connections. The definition is highly qualitative and subjective, however, and there is little evidence to suggest that the snugging procedure is adequate to ensure minimum preloads after final tightening. The procedures to achieve snug conditions do not necessarily guarantee uniform snug loads in the fasteners of a joint or between the fasteners of different joints. For instance, in a study conducted by Notch [4], the tensions in a sample of bolts snugged per the *Bolt Specification* guidelines varied from 0% to 43% of the minimum allowable preload. These variations in snug loads may be due to "human factors" such as an impact wrench operator's "feel" for snugging [5]. Additionally, it is unclear how factors such as plate out-of-flatness and plate orientation affect snug conditions and, therefore, final fastener tensions.

Doubts concerning the *Bolt Specification* extend not only to the uncertain definition of snugging, but also to the degree of compliance to the specification typically exhibited by field bolting crews. To address these issues, a limited number of studies have been undertaken, the results of which are described in the following section.

1.3 SUMMARY OF PREVIOUS RESEARCH

Most of the publications discovered in a literature search dealt with studies conducted on installed fasteners in existing structures to determine their preloads. When possible, the methods used by the bolting crews to install the fasteners were observed and compared with those mandated in the *Bolt Specification*.

Kulak and Obaia [3] investigated the installation of 7/8" diameter A325 bolts in three bridges under construction in the Canadian province of Alberta. Installation of the bolts was to be conducted using the turn-of-nut method. The researchers observed, however, that the bolting crews did not strictly follow the procedure. Installation was typically done with one application of the impact wrench with no snugging or marking of the nut for measured rotation past snug-tight. The crews indicated that this was the procedure they typically used for both large and small bridge structures. After observing the installation of several fasteners, testing was done to evaluate the tensile load in each. Ultrasound transducers were used to measure changes in bolt length due to installation. These elongations were, in turn, used to calculate load in the fastener. Of the 104 bolts so monitored, only 5 failed to meet the specified minimum value of preload required.

Notch [4] reported on the installed fastener tensions of 1" and 1-1/4" diameter A490 bolts used in the connections of a multistory building. A sample of ninety 1-1/4" diameter and twenty-two 1" diameter bolts of varying lengths was investigated. The average installed preload for the 1-1/4" fasteners was about 54% of the minimum required. The 1" diameter bolts also exhibited an average tension that was 54% of the required minimum. Measurement was conducted using the ultrasound method mentioned above. The report asserts that there were indications of improper techniques that had been used during the installation of the fasteners. Subsequently, Notch visited several nearby steel construction projects and observed that bolting crews were employing the turn-of-nut method with only a single installation pass to full tightening. This is similar to the procedure used by the ironworkers in the study by Kulak and Obaia. Additionally, Notch reported that instead of beginning fastener installation at the most rigid point in the connection and working to the free edges, most crews began bolting at random points in the connection.

In their report concerning failure characteristics of large bolted joints, Foreman and Rumpf [5] noted that the A325 bolts installed in their laboratory test connections by the turn-of-nut method had preloads exceeding the required values. Tension was measured by determining bolt elongation with a bolt extensometer and computing the load from predetermined calibration curves. The plates of the gripped material were nominally flat and not subjected to intentional deformation. Installation was conducted by two separate bolting crews which carefully adhered to the turn-of-nut procedures. Foreman and Rumpf indicated that comparison of the bolt elongations measured in the joints completed by each crew showed appreciable variation in the average elongation for each crew. Their measurements also indicated that deviations in length change for individual bolts done by a specific crew were minimal. The report suggests that the variations between the average elongation for each crew was due to differences in the "feel" of the installers for snugging operations. It should be noted here that differences in bolt elongations do not necessarily translate into differences in bolt tensile loads. When utilizing the turn-of-nut method, the bolt should end up on the relatively flat part of the load-elongation curve after yielding of the bolt threads. For this situation, changes in elongation have very little effect on fastener tension. Thus, the bolting crews could have greatly varying average elongations and still have all fasteners installed with comparable preloads which exceeded the required minimum.

From the above studies it is clear that there is evidence to suggest that field installation of fasteners is often not in accordance with the *Bolt Specification*. What is unclear, however, is the effect that improper installation has on fastener tensile loads. While Kulak and Obaia found that only about 5% of incorrectly installed fasteners failed to meet preload requirements, Notch found significant deficiencies in the preloads of the bolts in his sample. Overall, the results appear to be mixed and they demonstrate the need for further investigation of the subject.

The previous study which is most pertinent to this investigation was conducted by Birkemoe [6] at the University of Toronto. He conducted laboratory tests on both large moment connections and small lap joints with a particular emphasis on plate out-of-flatness. Both A325 and A490 bolts were used in the tests and elongation of the fasteners was measured by ultrasound methods.

In the large moment connections, the plates in the connection were nominally flat and installation was conducted by the calibrated wrench method using a hydraulic torque wrench.

Birkemoe noted that after snugging and the first tightening pass many of the bolts had lost a significant portion of their preload. This was especially true of the first few bolts in the installation sequence. After a second tightening pass, losses in fastener tension were again recorded but all final tensions were above the required minimum values.

The small lap joints were selected as being more typical of those found in bridge and building applications. For these tests, a joint was selected with two outer plates and a thicker middle plate which was intentionally deformed in both single and triple curvature. Deformations of the middle plate ranged from nominally flat conditions to about 5mm. Installation of the bolts was conducted by the turn-of-nut method. Test results showed that the deformed middle plate had a pronounced effect on the bolt tensions at both the snug tight and fully tight conditions. The tensions were reduced as the degree of plate distortion was increased.

Several reports were found, all of them based on internal studies by Huck International, Inc. [7,8,9], that addressed fastener tensions in proprietary lock-pin and collar fasteners (hereafter referred to as LPC fasteners). The Huck International Materials Testing Laboratory evaluated the preloads in individual C50L lock-pin and collar fasteners installed in nominally flat plates. Also investigated were the tensions in fasteners installed in grips containing a 5 degree beveled washer. Fastener diameters tested ranged from 1/2" to 1". The study found that the average installed tension for all size fasteners in flat plates exceeded the A325 minimum by 31%. With a 5 degree beveled washer under the collar, the average preload was 24% above minimum. Fasteners with a beveled washer under the head exhibited tensile loads 26% over the minimum required by RCSC.

Report TCT-89-7 [8] describes the testing of a welded tube flange joint for fastener tension loss in the 5/8" Huck fasteners with which the joint was connected. Preload in each LPC fastener was monitored during the installation of succeeding fasteners. The final tensions were observed to be over 40% above the minimum preload requirement.

The work of Birkemoe [6] indicates that out-of-flatness of the connected plates in certain joints can have an effect on the tensile loads in the joint fasteners. Preload variations can occur at any time during the installation process. The effect of out-of-flat plates on the installed tensions of LPC fasteners appears not to have been investigated in previous studies.

1.4 OBJECTIVES

The primary objective of this report is to investigate the installation requirements and characteristics of lock-pin and collar fastener groups in structural plate connections. These will be compared to the corresponding characteristics of conventional ASTM A325 fasteners in similar connections. The effects of a number of variables upon fastener tension will be studied. These include plate thickness, plate flatness, type of fastener used, and degree of snugging prior of final tightening. Conclusions will be drawn concerning the effects on snug and full-tight fastener tension of the aforementioned variables.

1.5 OVERVIEW OF RESEARCH CONDUCTED

Research for this report was divided into three main phases. These are as follows:

Phase I: Literature review.

Phase II: Evaluation and reliability studies of strain gauges proposed to measure fastener tension.

Phase III: Investigation of installation characteristics of fasteners through connection plate tests.

The findings and results of the literature review of Phase I were discussed in Section 1.3.

Phase II consisted of a series of tests which were conducted to determine the adequacy of strain gauges as a measuring device for fastener tension. Also investigated in these tests was a procedure to calibrate the gauged bolts to ensure correct readings of bolt tension.

In Phase III of the testing program, actual connection tests were performed to investigate the installed tensions of both the conventional A325 bolts and the Huck fasteners. These tests were separated into categories according to the type of fasteners used in a particular test, their method of installation, and the condition of the plates in the tested connection.

All tests were conducted at the Phil M. Ferguson Structural Engineering Laboratory at the University of Texas Balcones Research Center in Austin, Texas.

1.6 OVERVIEW OF REPORT

This report follows approximately the outline of the research detailed in the preceding section. The locations of the results of the various phases of research are as follows:

Phase I: (literature search) -- Section 1.3

Phase II: (evaluation tests) -- Chapter 3

Phase III: (connection plate tests) -- Chapters 4 and 5

Chapter 2 provides a brief description of the Huck International C50L fastening system used in the research program. Chapter 6 provides an overall summary of the results and conclusions of this study.

CHAPTER 2

THE HUCK INTERNATIONAL C50L FASTENING SYSTEM

2.1 GENERAL

The Huck International C50L fastening system is a lock-pin and collar fastener which falls under the RCSC *Bolt Specification* category of "Alternate Design Bolt". The C50L system consists of a pin which is inserted through a hole in the connected plates and a collar which is swaged onto the pin by a special installation tool. Tension control is provided by a break-neck which fractures at a given value of fastener tensile load. Hence, the title lock-pin and collar (LPC) fastener. An illustration of a Huck fastener is shown in Figure 2.1. Figure 2.2 shows a typical Huck fastener used in the study. This fastener may be compared to the conventional fastener components illustrated in Figure 2.3, which are typical of the conventional A325 fasteners used in this study.

The installation tool is hydraulically driven by a pump connected to the tool by high pressure hose. Figure 2.4 shows the installation rig supplied by Huck International for this research project. The front piece on the installation tool is the nose assembly which is unique for each diameter of fastener. Several different types of installation tools are available, depending on the application and size of fasteners to be installed. Hydraulic pumps come in both gasoline and electric powered models[10].

The C50L fastener conforms to the material and mechanical property requirements of the ASTM A325 specification [11] and is manufactured in diameters from 1/2" to 1-1/8". Fastener length is specified by a "grip number" which ranges from 4 for a 1/2" maximum grip size to a 92 which accommodates a 6" grip. Four different head styles are made for varying applications. These are shown in Figure 2.5. Also shown in the figure are the three types of collars that are available for the C50L pins [10].

2.2 INSTALLATION OF A C50L FASTENER

Figure 2.6 provides an illustrated step-by-step explanation of the installation of a C50L fastener. The illustration is reproduced from Reference 10.

2.3 COMMENTS ON THE C50L SYSTEM

The concept behind the C50L fastener, as with other Alternate Design Bolts, is to ensure adequate preload with a minimum amount of time and labor spent on both installation and inspection. Theoretically, inspection of the fastener should consist only of a visual check to make sure that the break-neck has fractured. No torque wrenches or other equipment should be needed. Additionally, installation time and the required worker skill level should decrease due to the ease of use of the C50L system.

An issue for these fasteners, as with any other bolt, is the effect that out-of-flat plates in a connection grip have on final installed fastener tensions. The intent of the *Bolt Specification* is that snugging of the fasteners minimize the effects of out-of-flat plates. However, the RCSC description of snug tight ("a few impacts of an impact wrench or the full effort of a man with an ordinary spud wrench") is ambiguous when applied to the Huck fastening system. Although snugging is required by the *Bolt Specification*, no appropriate means of achieving snug tight conditions are given. Neither an impact wrench nor a spud wrench is used during installation of a Huck fastener; therefore, the *Bolt Specification* provides little guidance in developing adequate snug loads.

Snugging by partially swaging a collar onto the lock-pin is possible by reducing the pressure of the hydraulic fluid driving the installation tool. The level of snug required to produce adequate final tensions has not, it appears, been investigated. A particular problem with the snugging of Huck LPC fasteners is that once the collar has been swaged into the first few grooves (the upper grooves, most distant from the grip) of the lock-pin, only a limited amount of additional elongation can be expected from the pin before the collar is fully swaged. The restricted ability of the pin to elongate translates into a finite amount of additional tension that can be induced in the fastener. This situation affects the tensile load that will be present in the fastener at full collar swage and pin-break. The more locking grooves that are initially engaged, the higher the snug load but the lower the additional tension that may be induced in the fastener during final installation. This situation is particularly important in applications with deformed or out-of-flat plates where adequate snugging is necessary to remove gaps in the plies of the connections.

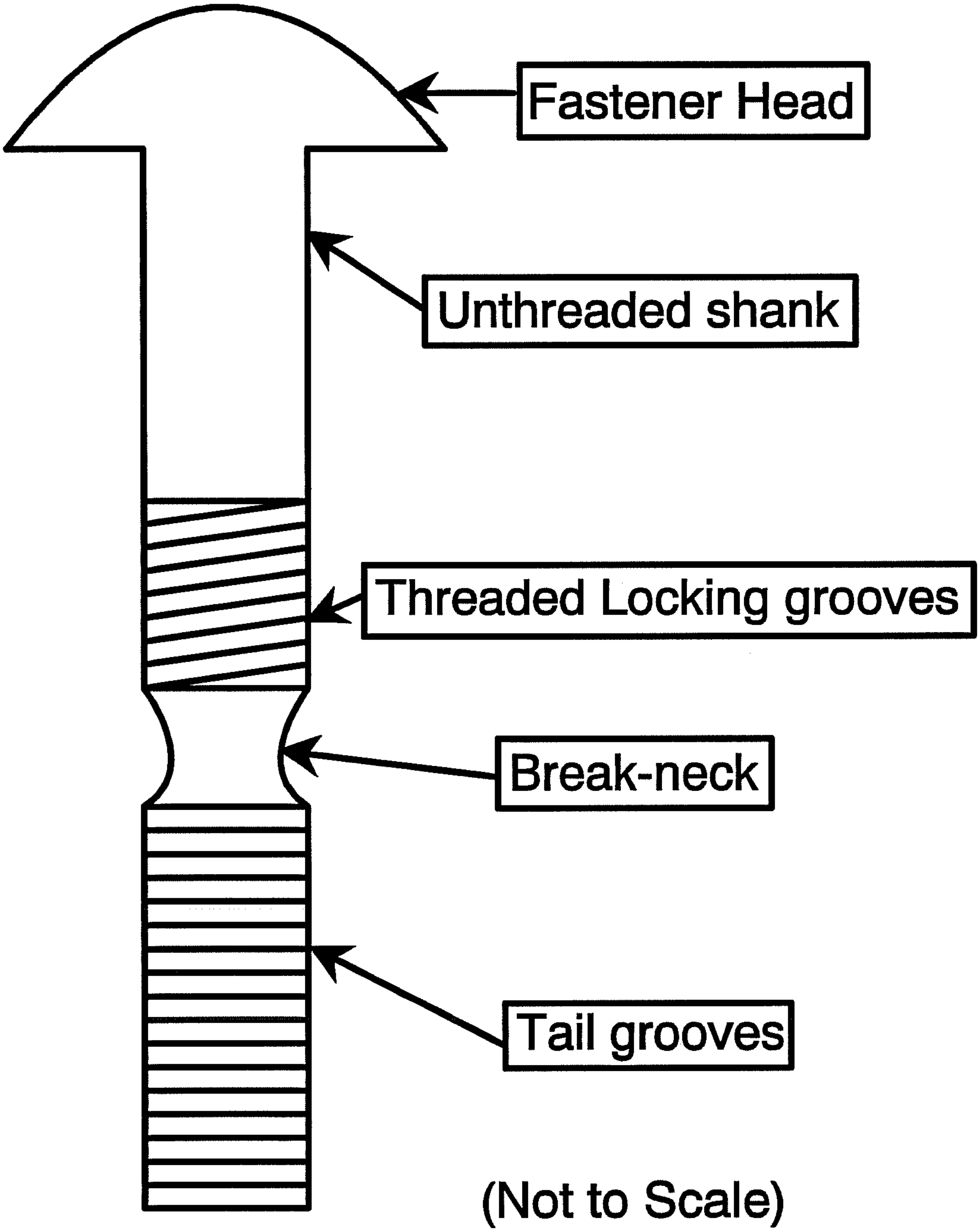


Figure 2.1: The Huck C50L Lock-pin

Figure 2.2: Huck C50L fastener and LC collar

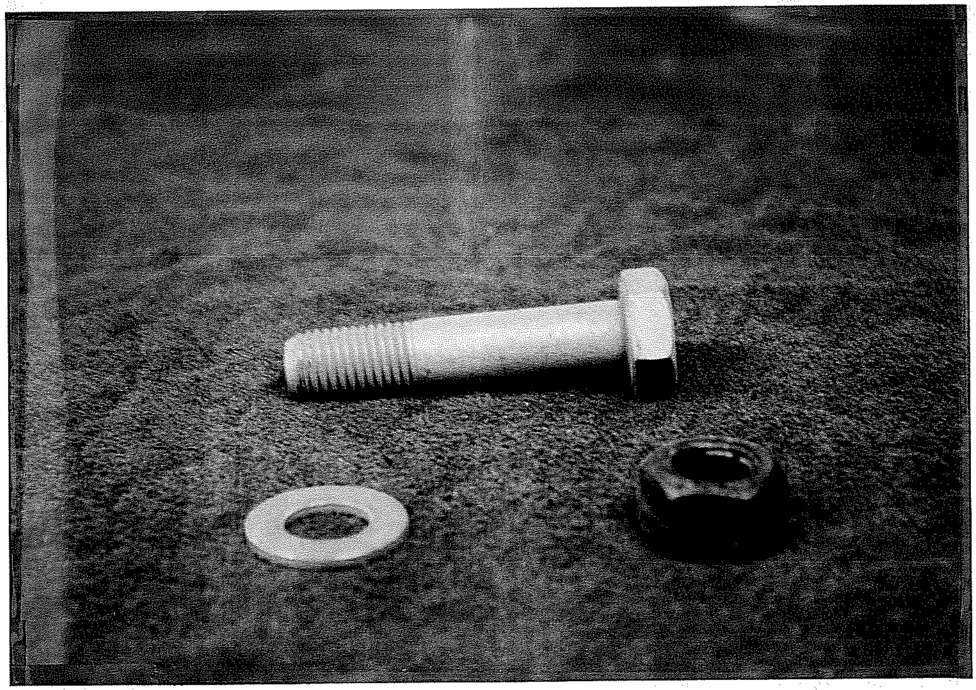


Figure 2.3: Conventional A325 fastener with 2H nut and hardened washer

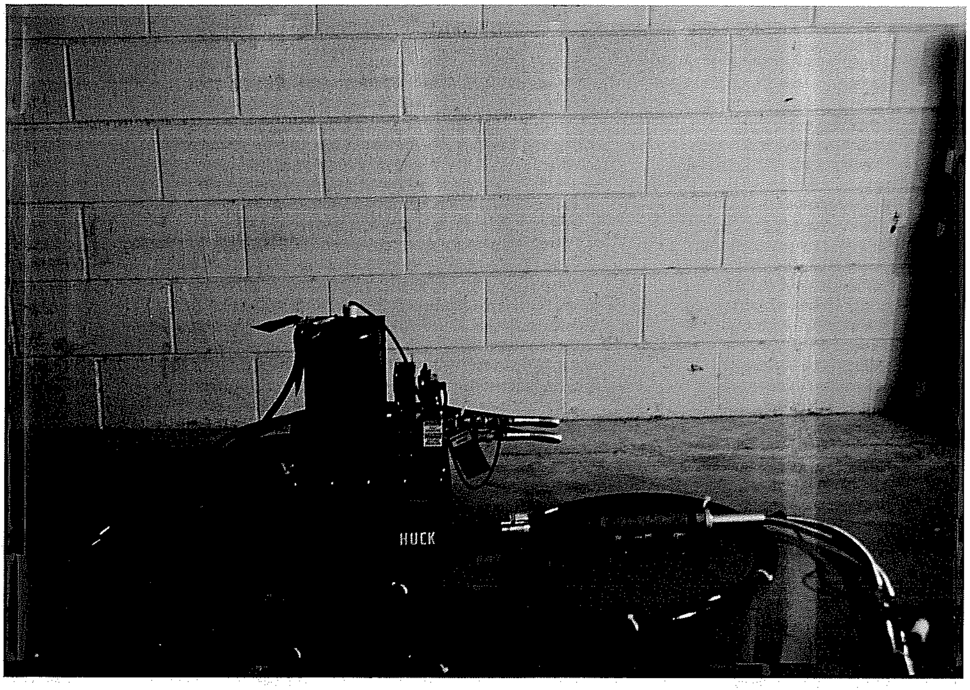
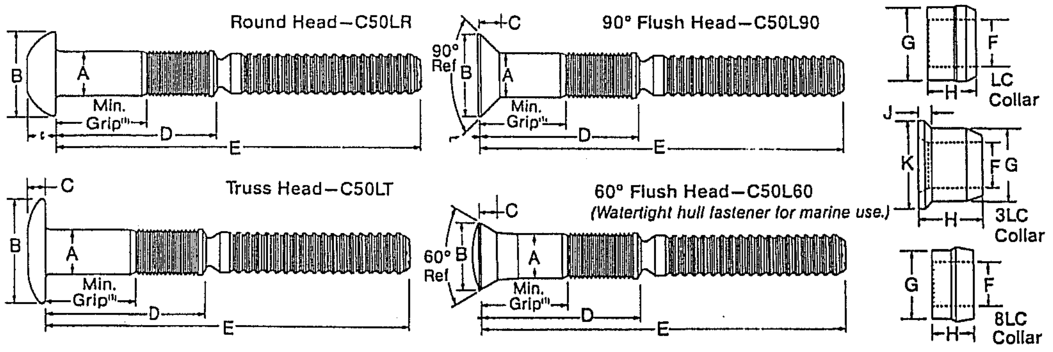


Figure 2.4: Huck installation tool and hydraulic pump



Fastener Dimensions

DIAMETER	A	ROUND HEAD (R)		TRUSS HEAD (T)		60° FLUSH HEAD (60)		90° FLUSH HEAD (90)	
		B	C	B	C	B	C	B	C
16 (1/2")	.515-.493	59/64	5/16	59/64	15/64	25/32	15/64	29/32	1/4
20 (5/8")	.642-.617	1-9/64	25/64	1-9/64	19/64	31/32	9/32	1-5/32	5/16
24 (3/4")	.768-.741	1-3/8	15/32	1-3/8	23/64	1-5/32	11/32	1-3/8	3/8
28 (7/8")	.895-.866	1-19/32	35/64	1-19/32	13/32	1-11/32	13/32	1-19/32	7/16
32 (1")	1.022-.990	1-53/64	39/64	1-53/64	15/32	1-17/32	15/32	1-27/32	1/2
36 (1-1/8")	1.149-1.098	2-1/16	11/16	–	–	–	–	–	–

Figure 2.5: Huck C50L fastener head styles

1. The fastener pin is inserted through a prepared hole. The collar is placed over the pintail of the fastener.
2. The nose assembly attached to the Huck installation tool is placed over the pintail.
3. Installation tool trigger is depressed, actuating tool "pull cycle." Chuck jaws, housed in nose assembly, grip pintail grooves. Tool piston and chuck jaws move rearward pulling pin into hole, seating head and removing gap from between work surfaces. Nose assembly outer sleeve (swage anvil) moves forward swaging collar material into pin's locking grooves.
4. When collar swaging is complete, tool continues to pull until the pintail breaks away from the pin. When the tool trigger is released, the nose assembly pushes off of the installed fastener and the installation cycle is completed.

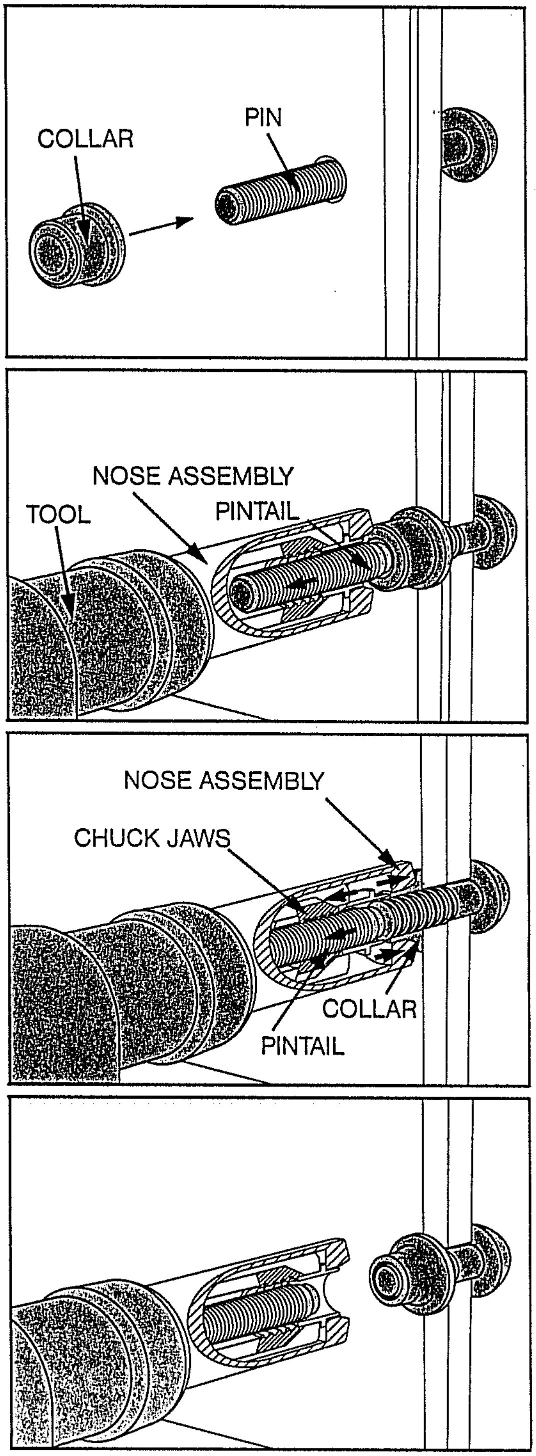


Figure 2.6: Huck fastener installation sequence

CHAPTER 3
EVALUATION/RELIABILITY TESTS FOR STRAIN GAUGED FASTENERS

3.1 GENERAL

A critical aspect of this research program was the ability to accurately monitor fastener tensions during all phases of installation. Prior to the commencement of actual connection tests a method had to be selected and verified as a suitable means to determine fastener tensile load. Several options were identified. One method used changes in bolt length to determine bolt tension through the use of careful calibrations. Another possible method was the use of electrical resistance strain gauges.

In several previous studies [3,4,6], ultrasound methods had been used to monitor fastener elongations. Fracture of the break-neck in the C50L fasteners, however, prevents the use of elongation as a basis for tension measurement. Thus, strain gauges were selected to measure fastener tension. Two strain gauge systems were evaluated for possible use. The first involved the use of conventional strain gauges applied to the fastener shank. The second system utilized a gauge made especially for bolt applications. The following is a brief description of both strain gauge types.

3.1.1 CONVENTIONAL STRAIN GAUGES

The first option for gauging bolts was to apply four conventional strain gauges to the surface of the fastener shank at locations 90 degrees apart around the diameter. An average of the four strain readings would be used as the axial strain at that cross-section of the bolt. For evaluating this technique, a gauge manufactured by Measurements Group, Inc. (gauge # EA-06-125UW-120) was chosen and installed with an adhesive and protective coating also made by Measurements Group. The adhesive was designated "M-Bond 200" and the protective coating applied to the gauge after installation was of the "M-Coat D" designation. Leadwires were soldered to the gauges after gauge installation and were routed up through holes drilled in the bolt head directly above the gauge location. The holes were drilled using a Lagun Republic model FTV-2S vertical milling machine. Figure 3.1 shows a conventional fastener instrumented in this manner.

The conventional gauges presented several problems. First, the holes in the bolt head were difficult to drill and resulted in many broken drill bits. In order to keep the leadwires from being pinched under the bolt head during installation, the holes were drilled so that the drill bit

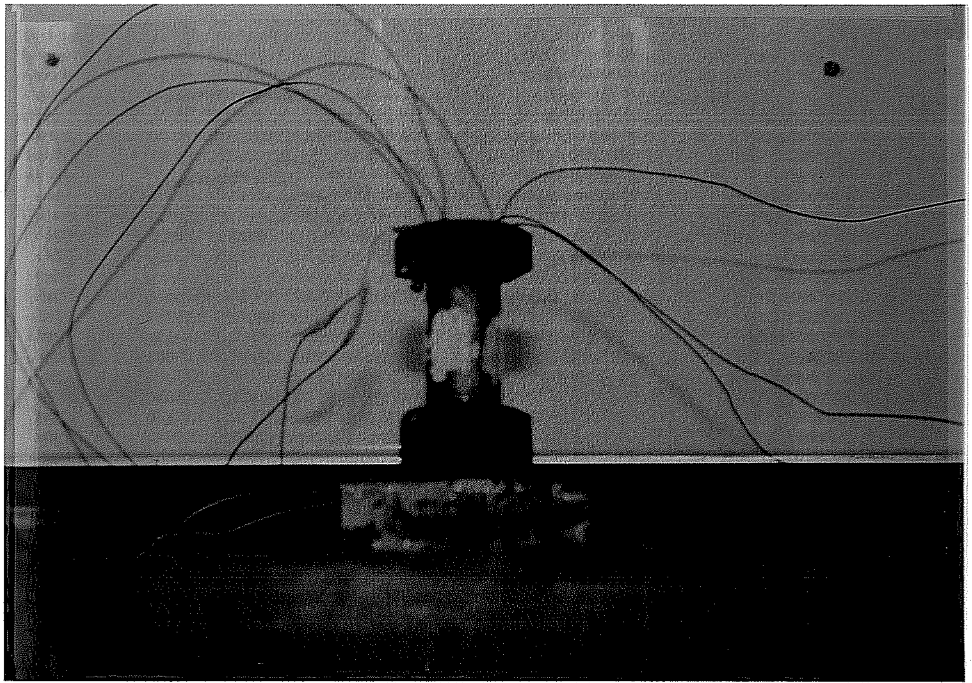


Figure 3.1: Conventional A325 fastener showing surface gauges and leadwires

exited the head very close to the shank. In fact, one-half of the bit was actually still in the shank of the bolt when it exited the bolt head. This tended to bend the drill bits and caused many to break in the hole, thereby rendering the bolt useless. The surface gauges also required a thorough cleaning of the bolt shank and removal of any galvanization at the gauge location before installation. Ultimately, the main concern was the interference problems encountered when installing the fasteners. The gauges (especially the soldered connections) tended to rub the sides of the plates into which they were installed and this resulted in broken gauges and grounding of the gauge to the gripped material.

3.1.2 SPECIAL "BOLT" GAUGES

These special gauges for bolt applications are produced by TML, a Japanese strain gauge manufacturer. The TML designation is "BTM-6C" although they will hereafter be referred to as the "BTM gauges". The gauges were purchased with pre-attached 3m leadwires. The BTM gauges were installed in a 2mm diameter hole drilled through the head of the fastener which is coincident with the longitudinal axis of the fastener. The drilling of all fasteners was done on a Sheldon 10" horizontal lathe. The depth of the hole depended upon the desired location of the gauge within the shank of the fastener. For this research study, the center of the BTM gauge was aligned with the center of the unthreaded portion of the shank of the bolt being gauged. For certain longer fasteners, this was not possible because the depth of drilling required exceeded the maximum drilling depth capacity of the lathe. For these fasteners, the BTM gauge was placed as close to the center of the unthreaded portion of the shank as possible.

Acetone was used to remove all excess cutting oil left over from the drilling operation and "M-Bond AE 15", adhesive made by Measurements Group, Inc., was used to install the BTM gauges in the hole. The adhesive was placed in the drilled hole using a 3cc syringe and a 15 gauge needle. After the gauge was inserted in the hole, the bolt was placed in an oven at 125 degrees Fahrenheit for 6 hours to cure the adhesive. The procedures used during installation were in accordance with those indicated by TML and Measurements Group.

The BTM gauges proved to be much easier and faster to install than the conventional gauges. The single gauge (vs. four) also provided fewer leadwires to become tangled, cut, or broken than did the surface gauges. Because they were installed inside of the fasteners, the BTM gauges were much less likely to suffer damage during handling of the bolts than were the conventional gauges. Overall, the BTM was the superior gauge with regard to installation and durability.

3.2 ISSUES CONCERNING THE USE OF STRAIN GAUGES

In order to use strain gauges to measure fastener tension, there must be a predictable relationship between gauge output and fastener tension. There are a number of concerns that had to be addressed in the evaluation/reliability tests. These concerns centered around the behavior of the gauges under the conditions that could be expected in the actual connection tests. Accordingly, the evaluation/reliability tests conducted on the fasteners sought to produce similar conditions so that an accurate comparison and assessment of each gauge type could be made.

Both during and after installation, the gauged fasteners (conventional A325's and Huck fasteners) experience large tensile loads. Tension, however, is not the only type of loading that the gauged fasteners could be expected to undergo. During the tightening of conventional A325 bolts, torsion due to rotation of the nut is induced in the bolt. Installation of fasteners in out-of-flat plates produces bending moments in the fasteners. The effects, if any, of these types of loadings on the relationship between fastener tension and strain gauge output were unclear.

A second concern was the effect of yielding of the fastener on the strain gauge(s). Yielding of the fastener in the region occupied by the gauge(s) will result in a non-linear relationship between tension and strain and render tension measurements inaccurate. As noted in Section 1.2, the turn-of-nut method of installation will induce yielding in the threaded portion of conventional A325 bolts [2]. Yielding, therefore, is a concern that must be evaluated for bolts tightened by the turn-of-nut method and may also be a factor in fasteners installed by different procedures. It was believed that the unthreaded shank of the fasteners would stay linear during installation operations and that yielding would be confined to the threaded (or grooved) areas of the fasteners. This supposition did, however, require experimental verification.

During the installation of the fasteners, especially in out-of-flat plates, it was expected that tensile loads would cycle as fasteners lost their preloads and were retightened. It was uncertain whether cycling could have an effect on strain gauge performance. The fracture of the break-neck on the Huck fasteners was an additional issue due to the sudden nature of the separation. Disturbance of the bond between the BTM gauge adhesive and the fastener material was seen as a possible consequence of Huck fastener installation. These concerns then, formed the rationale behind the evaluation/reliability tests on the strain gauged fasteners.

3.3 OVERVIEW OF TESTS PERFORMED

To address the above concerns, a number of tests were conducted which subjected the conventional A325 and Huck fasteners to a variety of different loadings. These are summarized as follows:

Conventional A325 fasteners:

1.) Direct tension
2.) Torqued tension
3.) Torqued tension and bending
4.) Torqued tension to bolt yield
5.) Torqued tension and bending to bolt yield

Huck International C50L fasteners:

1.) Direct tension on uninstalled fasteners
2.) Direct tension on installed fasteners
3.) Direct tension and bending on installed fasteners

The diameter of all fasteners tested was 7/8" (minimum preload= 39 kips). Conventional A325 bolt lengths tested were 3-1/4" and 5". Huck fastener grip lengths were 32 and 48 (used for 2" and 3" overall grips) which were used with 3LC collars.

All testing was performed in either a Skidmore-Wilhelm bolt tension indicator (model # ML) or a Satec Systems 600 kip tension/compression test machine. Both were calibrated to a National Institute of Standards and Technology certified load cell prior to the start of testing.

In the strain gauge evaluation/reliability tests for conventional A325 fasteners described in Section 3.4, gauged fasteners were first loaded to about 45 kips in direct tension. This provided the relationship between tension and gauge output that would be obtained from a typical fastener. The gauged conventional fasteners were then loaded to about 45 kips in torqued tension, and torqued tension and bending. This simulated the loading that would be expected during a calibrated wrench installation sequence. Gauged fasteners were then loaded to higher levels of tension that caused yielding of the fastener to simulate conditions expected in a turn-of-nut installation. For these tests, the fasteners were subjected to torqued tension, and torqued tension and bending, with several tests continued to fastener failure.

In the strain gauge evaluation/reliability tests for Huck fasteners described in Section 3.5, gauged fasteners were first loaded to about 30 kips in direct tension, to provide a typical fastener tension vs. gauge strain relationship. Gauged Huck fasteners were then installed in a Skidmore, with the collar fully swaged onto the pin using the Huck installation tool. The fasteners were then loaded to approximately 50 to 55 kips, in direct tension, and in direct tension and bending. This level of loading was near the tensile strength of the fastener, and was well beyond the load expected in the actual connection tests. Loading of the fasteners was accomplished through the Skidmore, as described in Section 3.5.2.

The following sections detail the specific tests performed to verify and evaluate strain gauge performance.

3.4 TESTS ON CONVENTIONAL A325 FASTENERS

Conventional A325 bolts were the initial fasteners investigated during the evaluation/reliability test phase. For the tests, each fastener was instrumented with both the four surface gauges and the single BTM bolt gauge so that a comparison of the two types could be made. All tests were performed on 7/8" A325 bolts with a non-galvanized or "black" finish, except as indicated. All of the black bolts were from the same production lot. As noted previously, bolt lengths studied were 3-1/4" and 5". The nuts used with the conventional A325 fasteners were ASTM A194, Grade 2H. All washers were specified to meet the requirements of ASTM F436.

Prior to the start of the testing program on the strain gauged fasteners, a preliminary test was conducted to determine the tensile load at which yielding of the black conventional A325 fasteners began. A single, ungauged fastener was loaded in direct tension in the 600 kip Satec test machine. Applied load was read directly from the machine and a dial gauge was used to record movement of the machine deck. A typical tension versus elongation curve for the black A325 fastener is shown in Fig. 3.2. Yielding of the fastener initiated at about 50 kips.

Tensioning of the fastener in the 600 kip machine was accomplished using a special test jig supplied by Huck International (hereafter to be known as the Huck tensioning jig). A photograph of this apparatus with an installed 7/8" conventional A325 fastener can be seen in Figure 3.3. The jig in the photo is under the compression head of the Satec 600 kip test machine. The tension jig allows the compressive force of the Satec machine to be translated into tensile load in the fastener installed in the jig. The "legs" of the top and bottom halves of the jig react against a pair of high strength steel plates into which the specimen is installed. This induces separation of the plates and, consequently, tension in the fastener. The conventional A325 fasteners were installed in the plates with the 2H nuts described above. This procedure was used on the conventional A325 fasteners in all direct tension applications.

In all of the following evaluation/reliability tests, loads were cycled to simulate fastener loading and unloading during actual installation. A chart showing a typical load history for a conventional A325 fastener is shown in Figure 3.4.

All fasteners used in the tests described hereafter were strain gauged fasteners. The gauge strains for all tests were recorded using a digital data acquisition system consisting of a Hewlett Packard 3852 data acquisition unit (w/digital voltmeter and multiplexer), constant voltage power supply, and a 286 AT IBM compatible computer. Figure 3.5 shows the Satec 600 kip machine and the digital data acquisition system. The data acquisition system is in the brown cabinet on the left side of the photo.

3.4.1 DIRECT TENSION TESTS

The direct tension tests were performed in the Satec 600 kip machine with the Huck tensioning jig described at the beginning of this section to induce tension in the bolt. Values of machine load were read directly from the machine into the data acquisition system.

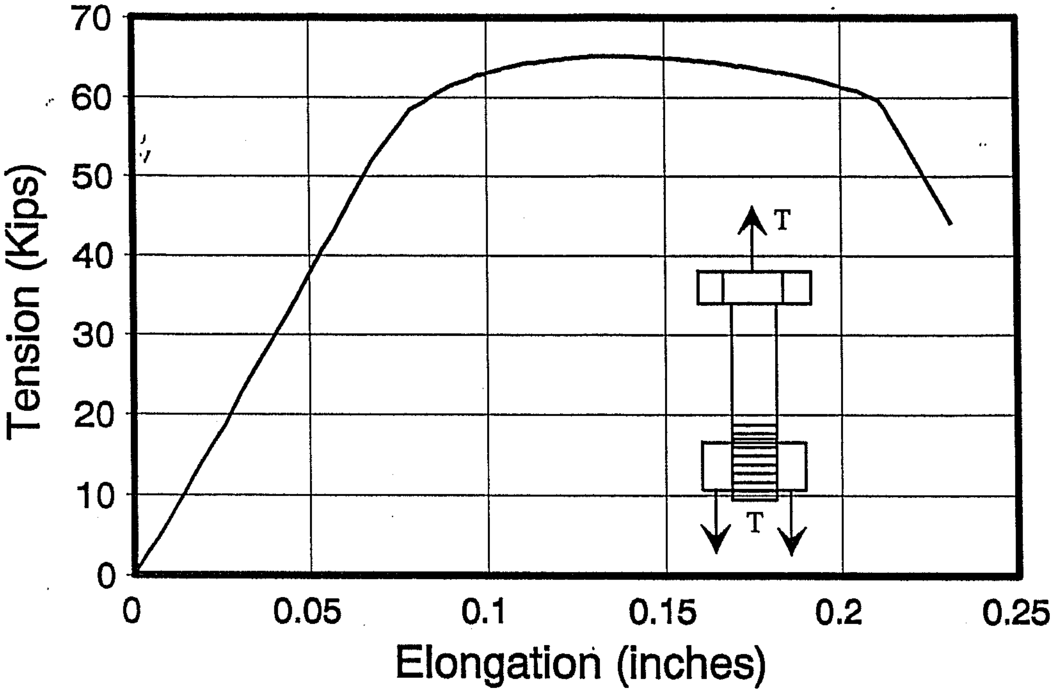


Figure 3.2: Tension vs. elongation for a typical conventional A325 fastener

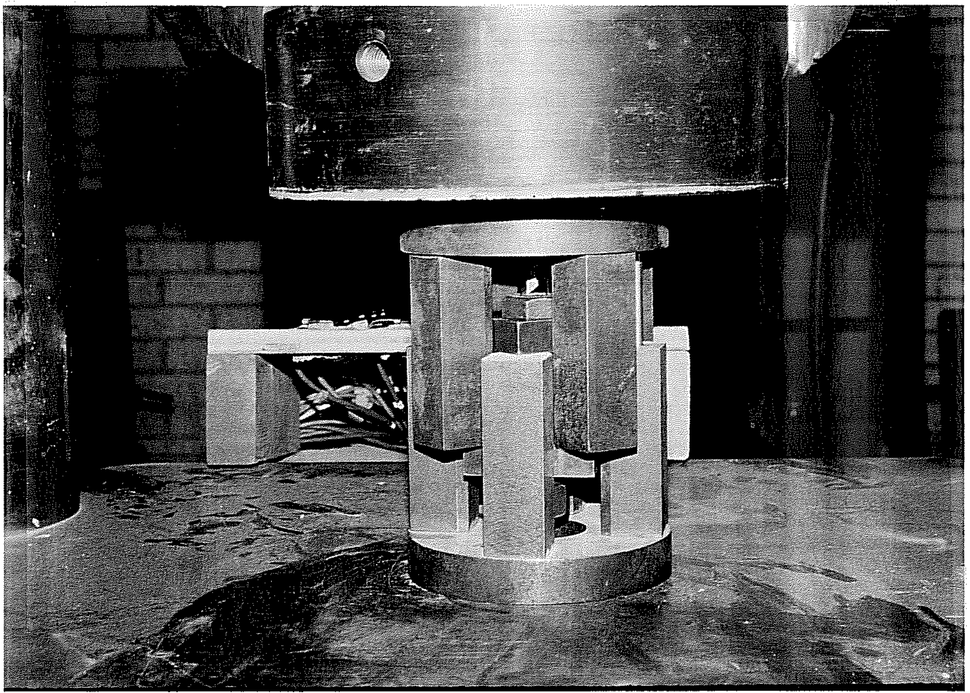


Figure 3.3: Huck tensioning jig with installed fastener

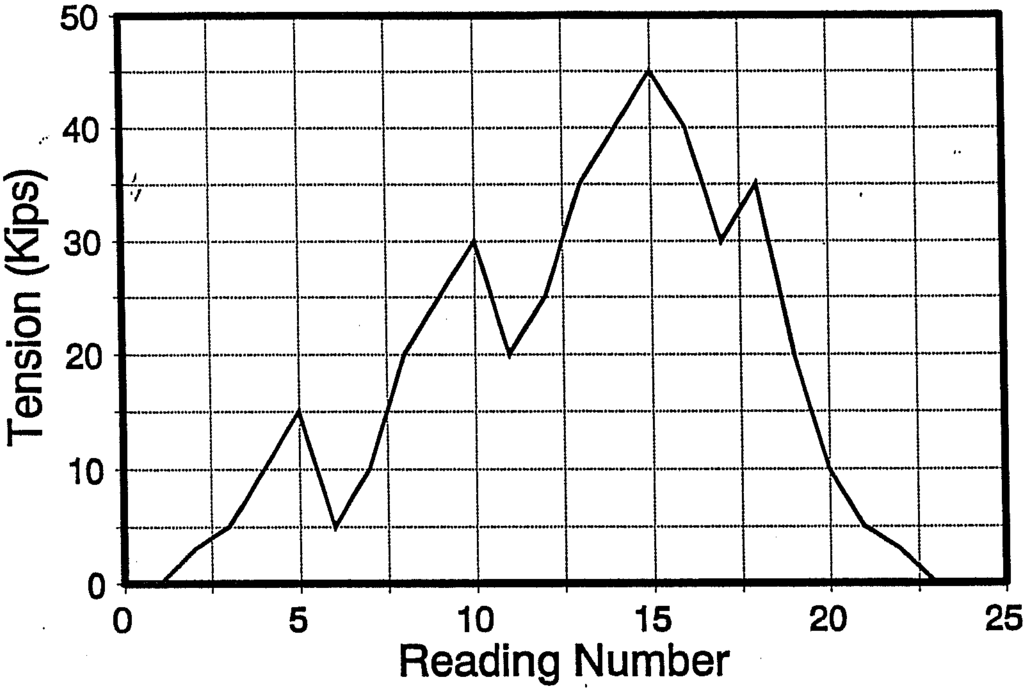


Figure 3.4: Typical load history for a conventional A325 fastener

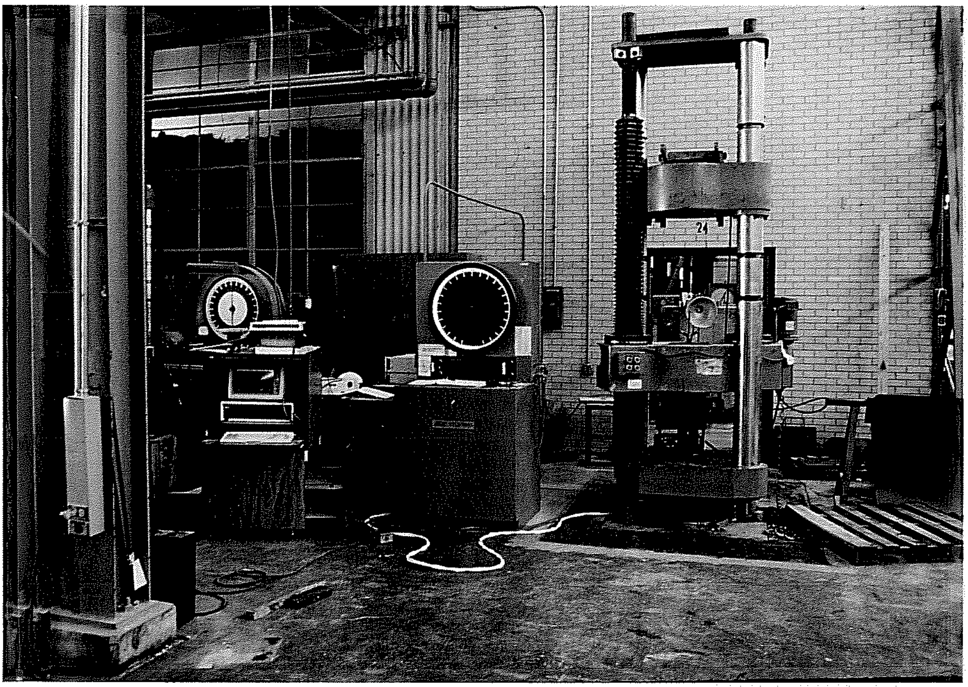


Figure 3.5: Digital data acquisition system and 600 kip Satec testing machine

Figures 3.6 and 3.7 show the results of the direct tension tests on the A325 bolts. As can be seen, the curves for both lengths of bolt are very linear up to the maximum test load of 45 kips. In addition, the values of the BTM gauge strain and the average of the four surface gauge strains agree closely for any given level of load. The maximum deviation between the two gauge readings is about 1.5 kips for the 5" A325 at about 2500 microstrain (1 microstrain = 10^{-6} in./in.).

3.4.2 TORQUED TENSION TESTS

The torqued tension tests were conducted using the Skidmore-Wilhelm bolt tension indicator to measure the fastener load. Hardened washers were used to build up the appropriate grip size for the 3-1/4" and 5" bolts. A pressure transducer was installed in the exterior pressure fitting of the Skidmore which allowed an electronic reading of fastener tension in the Skidmore. Torque was applied to the bolts with an ordinary spud wrench. Figure 3.8 shows the set-up for the torqued tension tests. Note the external pressure transducer and installed conventional A325 bolt.

Figures 3.9 and 3.10 present the results of the torqued tension tests. The graphs of gauge strain(s) vs. load show that there is good agreement between the output of the two gauge types, especially for the 3-1/4" bolt test. For the 5" bolt, the discrepancy in strain readings for a given load is greater, although the maximum difference is only about 2 kips. At high levels of applied load, say 35 to 45 kips, some minimal gauge hysteresis in apparent.

3.4.3 TORQUED TENSION TESTS WITH BENDING

These tests were conducted in the same manner as those in Section 3.4.2 except that a beveled washer was used under the nut on the conventional A325 fastener to induce bending in the bolt. A washer with a 2.86 degree bevel was machined for the application and placed under the nut. The 2.86 degree bevel was selected to produce more severe bending than would be experienced by fasteners installed in the out-of-flat plates to be investigated in the connection tests (Phase III). See Figure 3.8 for a photograph of this test set-up. Note the beveled washer under the nut.

The results of the torqued tension with bending tests are shown in Figures 3.11 to 3.12. The plots are very linear up to the 45 kip load to which the fasteners were tightened. Also apparent is the close agreement of the curves of the BTM gauge strain and the surface gauge

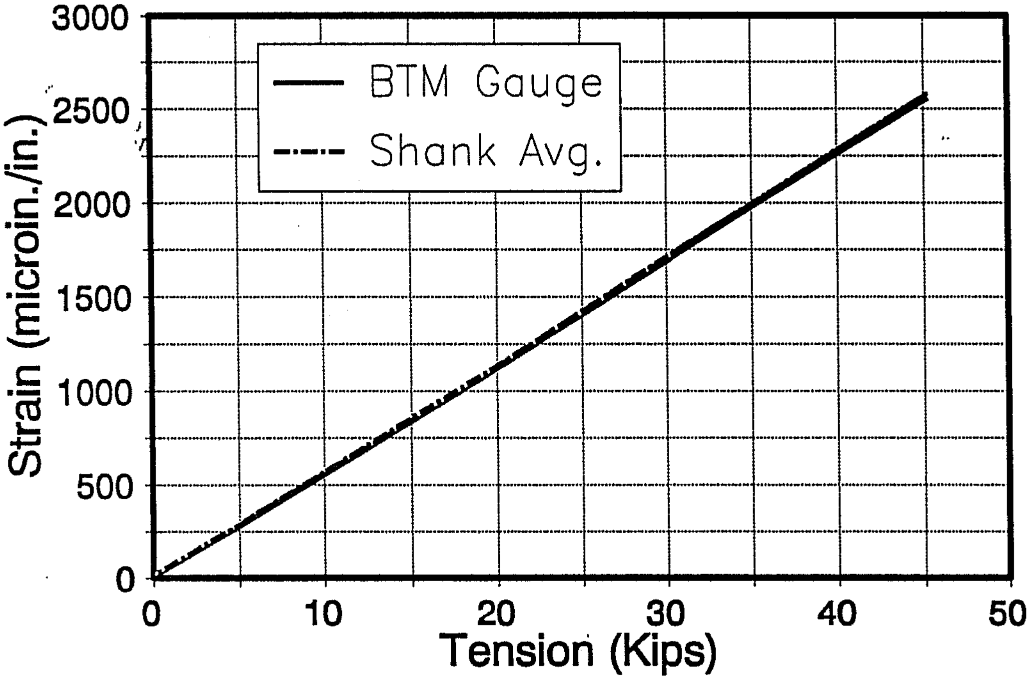


Figure 3.6: Tension vs. strain for 3-1/4" conventional A325 in direct tension

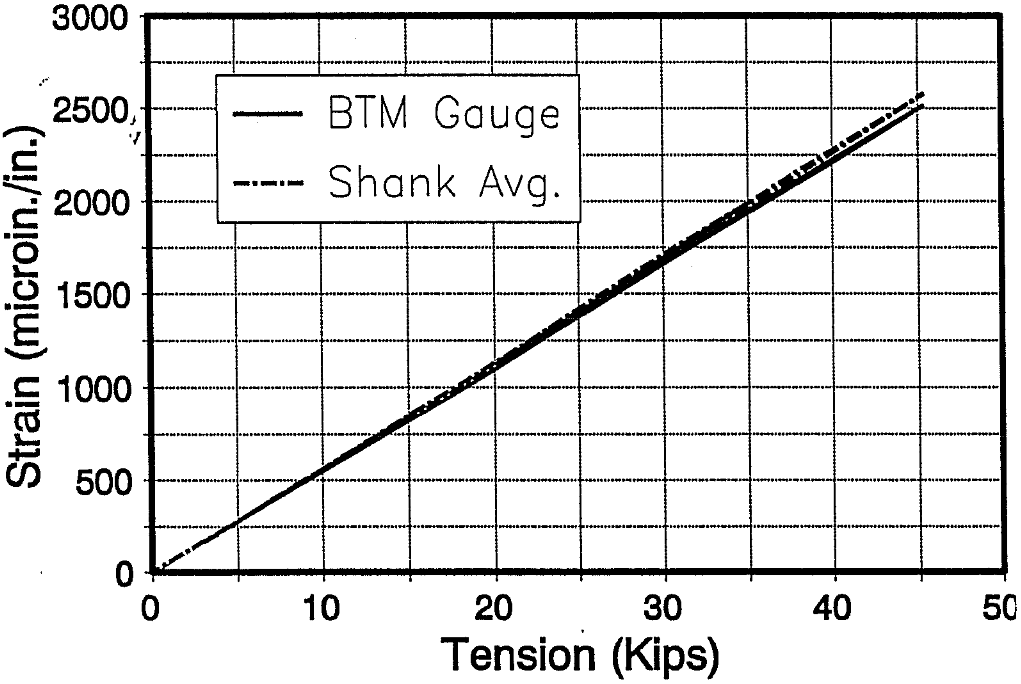


Figure 3.7: Tension vs. strain for 5" conventional A325 in direct tension

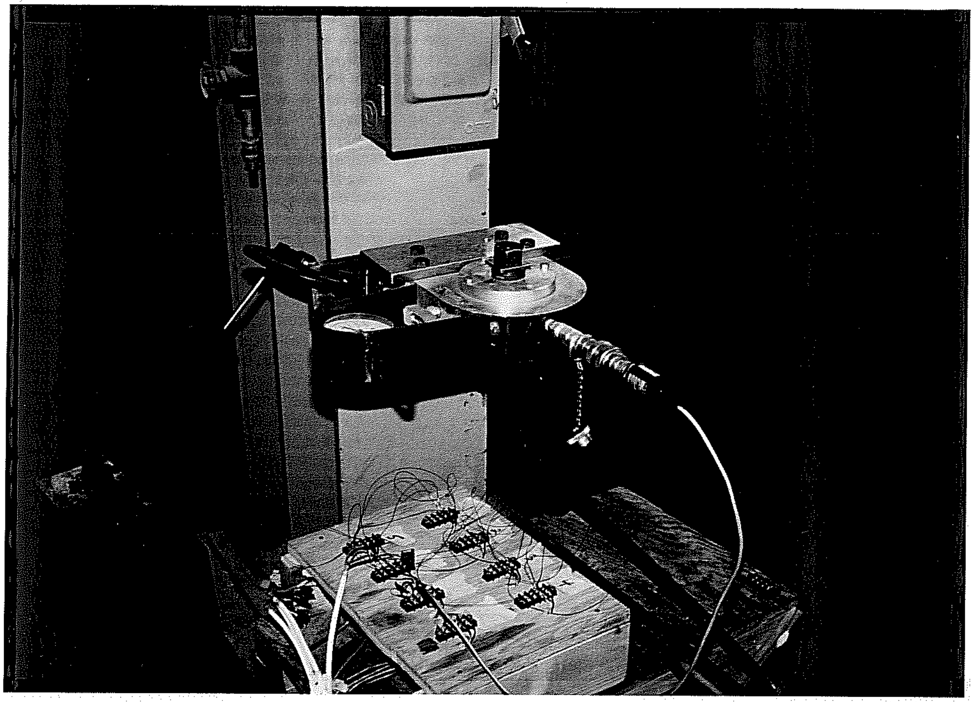


Figure 3.8: Set-up for torqued tension evaluation/reliability tests

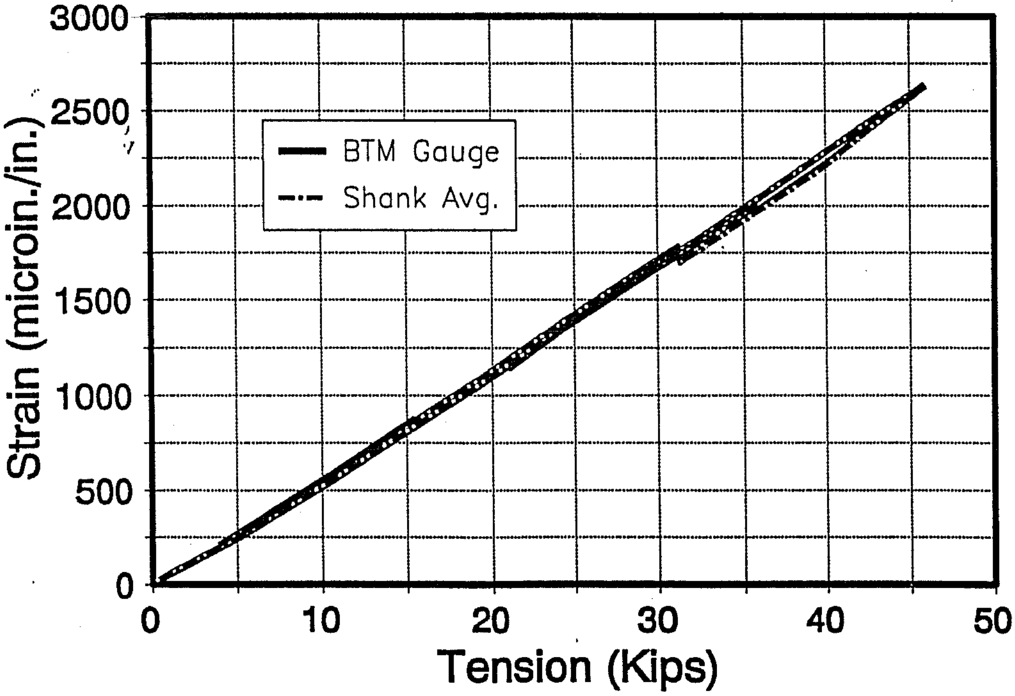


Figure 3.9: Tension vs. strain for 3-1/4" conventional A325 in torqued tension

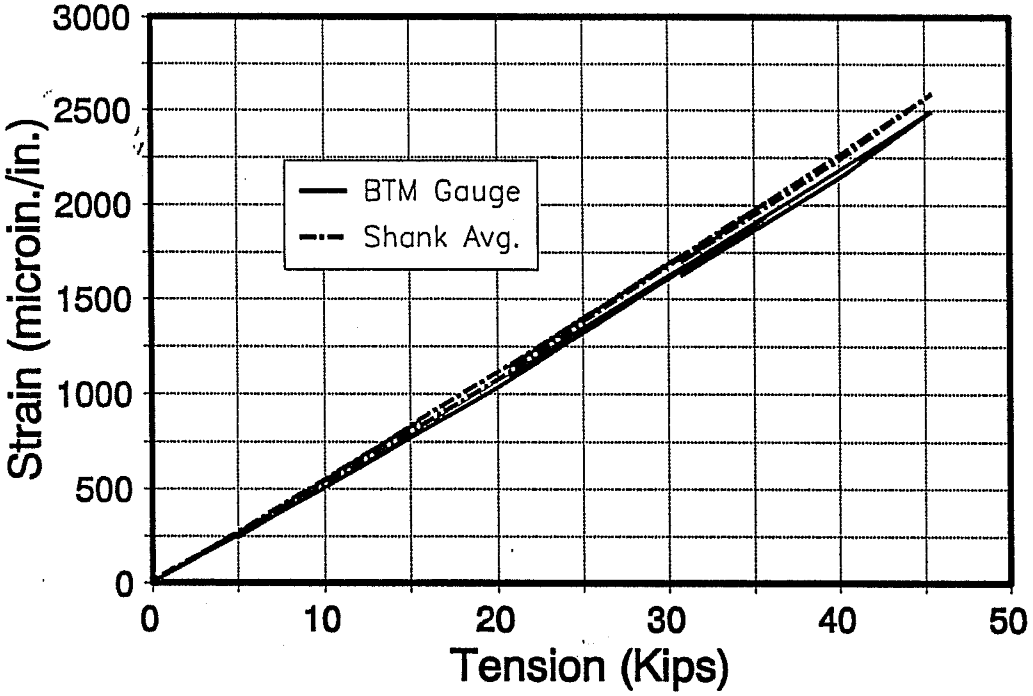


Figure 3.10: Tension vs. strain for 5" conventional A325 in torqued tension

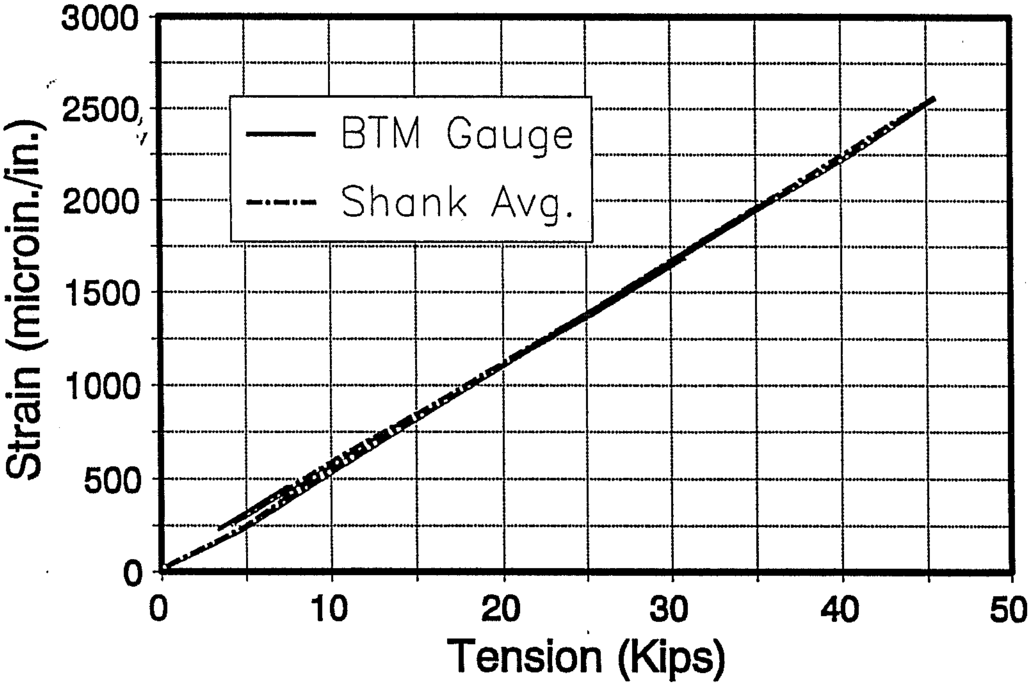


Figure 3.11: Tension vs. strain for 3-1/4" conventional A325 in torqued tension & bending

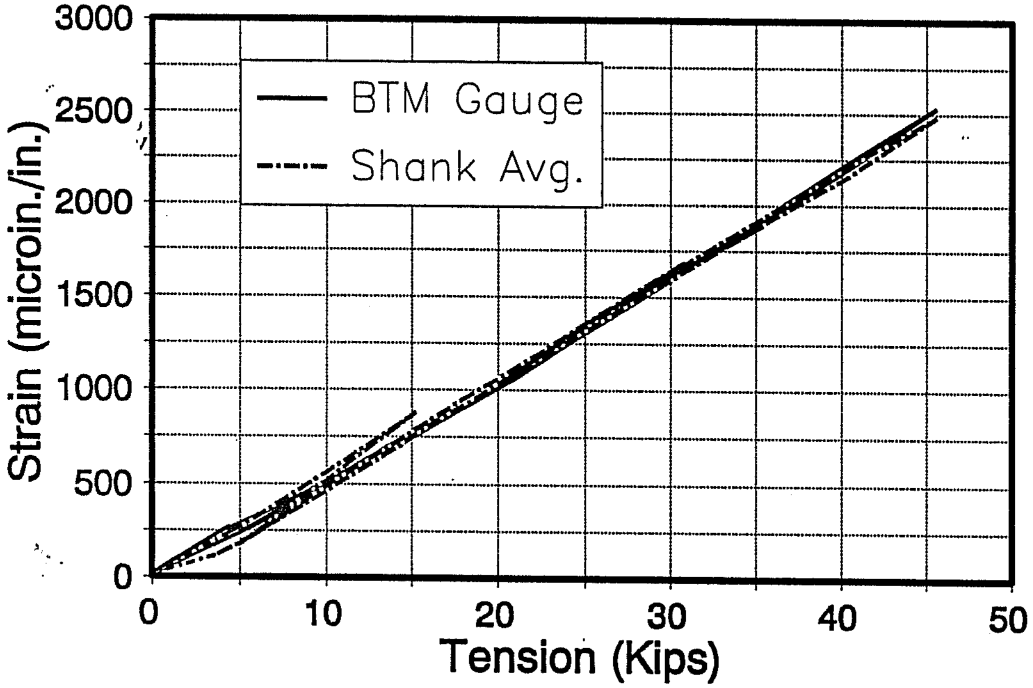


Figure 3.12: Tension vs. strain for 5" conventional A325 in torqued tension & bending

average strain output. For a given value of strain, the two gauge types indicate tensile load to within about 2 kips of each other. Gauge hysteresis is minimal, with the maximum deviation at a given strain value being about 1 kip for the 5" fastener.

3.4.4 TORQUED TENSION TESTS TO BOLT YIELD

Two galvanized A325 bolts (4-1/4" length) were evaluated in these tests, in addition to the 3-1/4" and 5" black bolts. These galvanized bolts were taken from the same lots as the bolts used in the connection tests described in Chapter 4. The galvanized bolts were instrumented with only the BTM gauges. One of the galvanized fasteners was used with a well lubricated nut while the other was paired with a nut almost devoid of thread lubrication. This was done to induce different magnitudes of torsional shear into the bolts. The test set-up was identical to that of Section 3.4.2 except that torque was applied to the black bolts with an impact wrench and to the galvanized bolts with a torque wrench coupled with a torque multiplier. Load was applied to the black bolts until fracture occurred in the bolt threads. The galvanized fasteners were torqued until yield was induced (i.e. it was apparent that the bolts were taking no more tensile load with increased nut rotation).

The results of these tests are presented in Figures 3.13 to 3.16. For the black bolts (Figures 3.13 and 3.14), the curves of gauge strain vs. load stay linear up to the point of bolt failure by fracture in the bolt threads. For a specific value of strain, the maximum difference between the load predicted by the BTM gauge and the surface gauges is about 2 kips. For the 3-1/4" bolt, some gauge hysteresis is noted at high levels of load. The effects of this hysteresis are minimal (about 1-1.5 kips for a given strain level) and do not significantly affect the loads predicted by the strain gauge(s).

The galvanized bolt with the lubricated nut did not stay elastic in the unthreaded portion of the shank although the plot in Figure 3.15 appears to indicate a linear relationship between bolt tension and strain gauge output. Upon unloading of the fastener, the BTM gauge read a residual strain of about 30 microstrain which indicates a small amount of yielding in the unthreaded shank.

The galvanized bolt with the unlubricated nut did not exhibit yielding in the unthreaded shank because it began to yield in the threads at a relatively low value of tensile load. As shown in Figure 3.16, the yield load is about 47 kips, as compared to the 55 kip yield load for the galvanized bolt with the well-lubricated nut. Note that both galvanized bolts were taken from the same lot.

These tests indicated that some yielding can occur in the unthreaded portion of the fastener at high levels of tension, when the fastener is subjected to torqued tension. It is interesting that the galvanized bolt with the lubricated nut exhibited yielding while the galvanized bolt with the unlubricated nut did not. A possible explanation is the differing conditions of the lubrication between the bolts and the nuts inducing different amounts of torsion in the bolts. Higher torsional loads for the unlubricated nut appear to have caused yielding in the threads at lower values of tension which, in turn, left the shank elastic.

3.4.5 TORQUED TENSION TESTS WITH BENDING TO BOLT YIELD

These tests were similar to the tests of Section 3.4.4 except that the 2.86 degree beveled washer was installed under the nut of each fastener to induce bending in the bolts. One black bolt of each length was tightened to bolt failure while both load and gauge strain were monitored. For these tests, the bolts failed due to thread stripping.

Figures 3.17 to 3.18 present the results of the torqued tension with bending to bolt yield tests. For the 5" conventional A325 fastener, there is some observed offset between the readings from the BTM gauges and the surface gauges. Both types of gauge, however, exhibit nearly linear

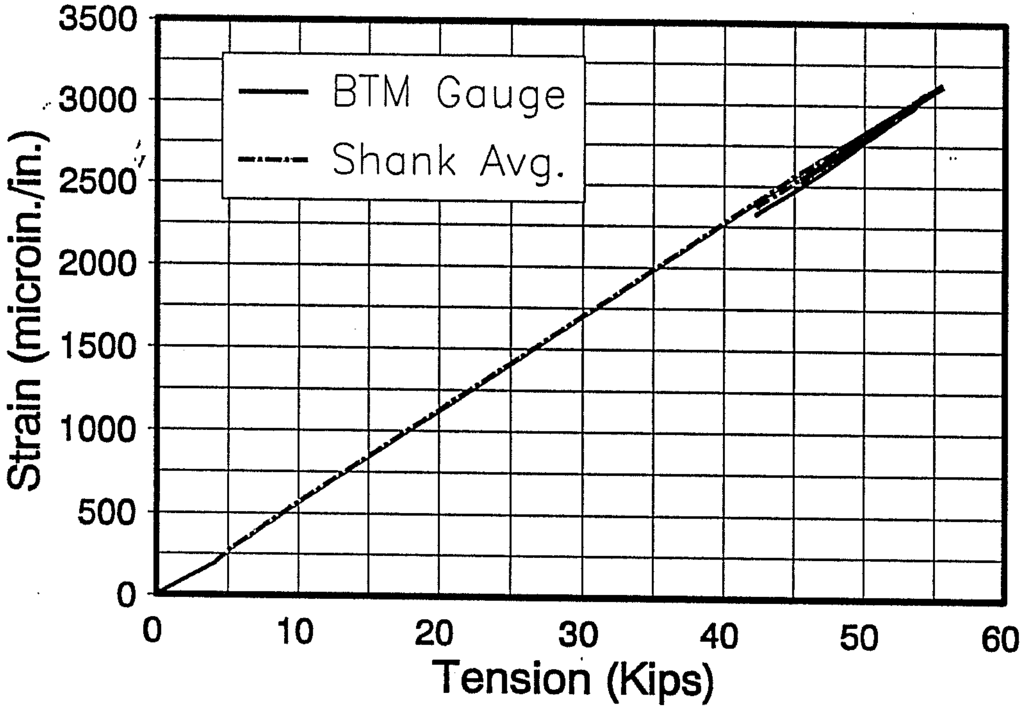


Figure 3.13: Tension vs. strain for 3-1/4" black A325 bolt in torqued tension to bolt failure

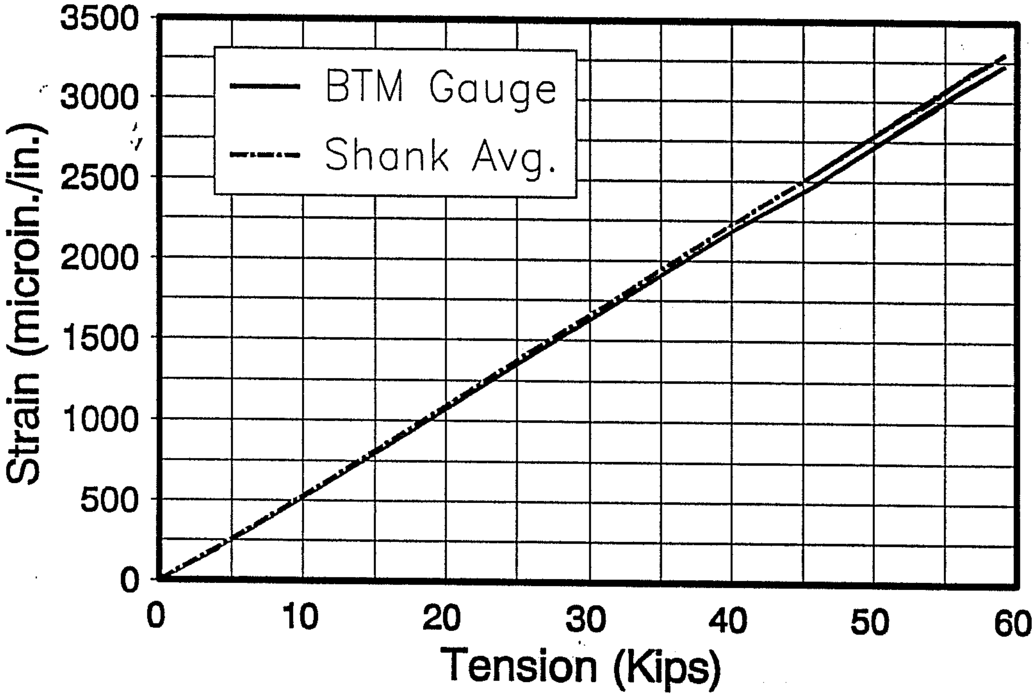


Figure 3.14: Tension vs. strain for 5" black A325 bolt in torqued tension to bolt failure

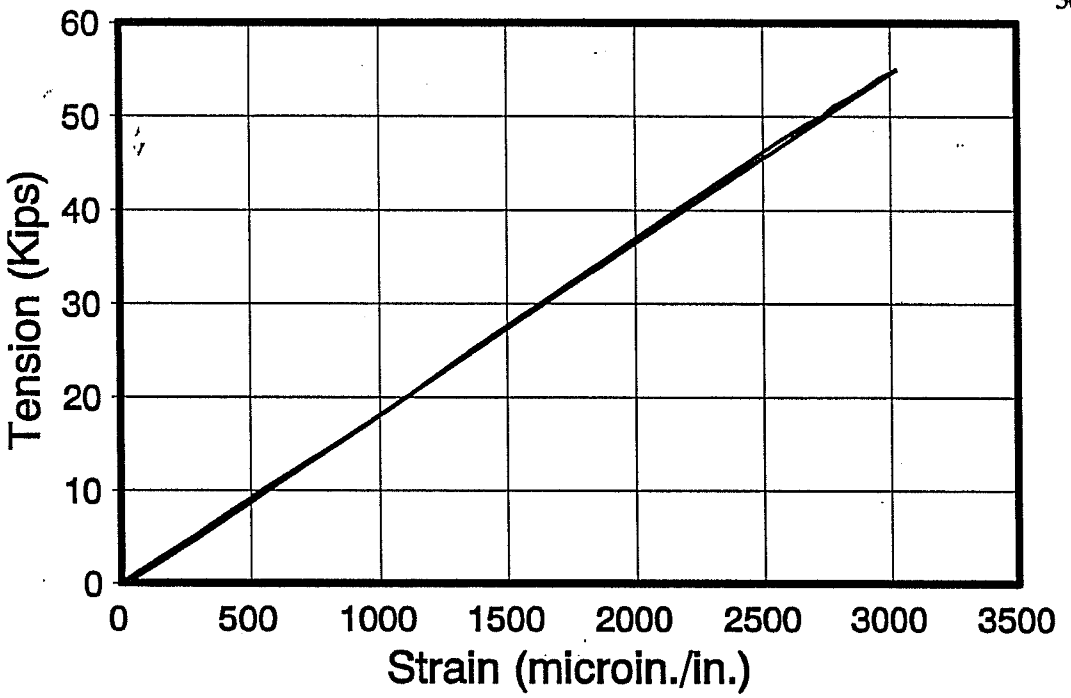


Figure 3.15: 4-1/4" galvanized A325 in torqued tension to bolt failure - lubricated nut

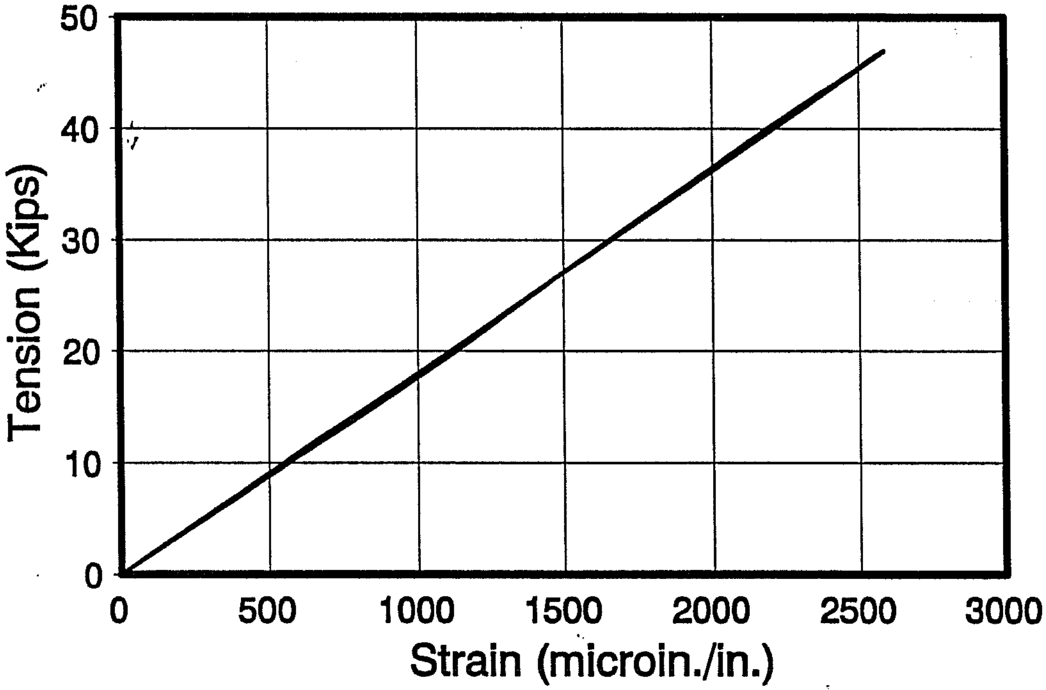


Figure 3.16: 4-1/4" galvanized A325 in torqued tension to bolt failure - unlubricated nut

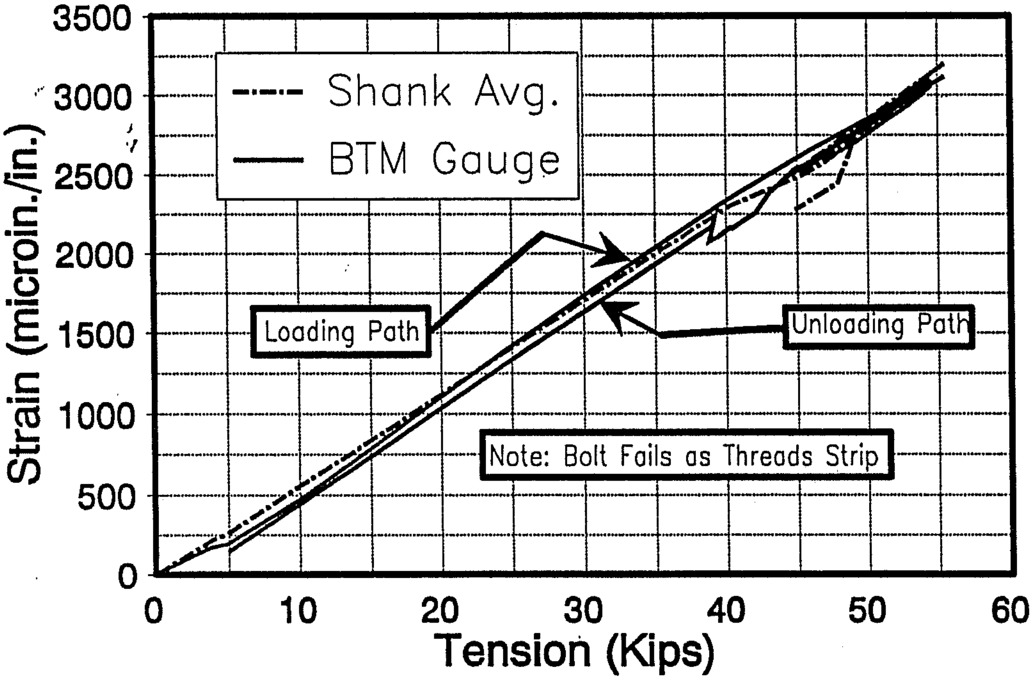


Figure 3.17: Tension vs strain for 3-1/4" A325 bolt in torqued tension & bending to bolt failure

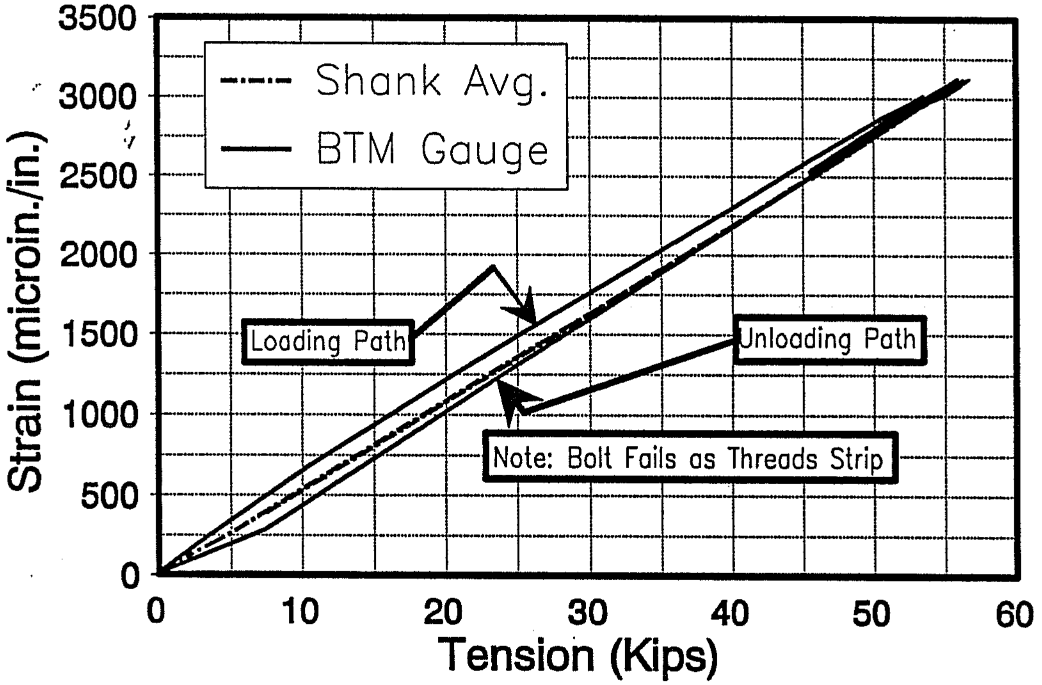


Figure 3.18: Tension vs strain for 5" A325 bolt in torqued tension & bending to bolt failure

behavior up to about 50 kips in both loading and unloading. At higher loads, though, the gauge readings (both types of gauge) became unpredictable and unusable as thread stripping occurred. Most importantly, however, at the lower levels of load, the load vs. strain relationship was nearly linear and quite acceptable for the accurate measurement of bolt tensions.

3.4.6 CONCLUSIONS OF THE CONVENTIONAL BOLT TESTS

From the results of the tests described in Section 3.4, certain conclusions may be drawn. They are as follows:

1.) For a given value of load, the strain readings from both the average of the surface gauges and the BTM gauge agree favorably. This condition holds for fasteners subjected to a variety of loadings including direct tension, torqued tension, and torqued tension combined with bending. Figures 3.19 through 3.22 show comparisons of measured gauge stains for the BTM type gauges under different load conditions. The curves of direct tension vs. torqued tension and direct tension vs. tension with bending are almost concurrent. As can be seen, the effects of both torsional shear and bending appear to be minimal on the output of both types of strain gauges. Thus, a calibration based on direct tension is not invalidated by torque or bending in the bolt.

2.) Cyclic loads do not have a significant adverse effect on strain gauge output. None of the plots of gauge strain vs. applied load, for any loading condition or strain gauge type, show any appreciable hysteresis effects. The maximum error due to hysteresis in the gauge output is about 1.5 kips. Thus, the gauges can be assumed to be reliable monitors of fastener tension during the loading and unloading cycles expected during installation.

3.) For all load conditions, the relationship between measured strain and applied load is essentially linear to values of load in excess of 45 kips. For certain fasteners, namely the black conventional bolts, load vs. strain curves stay linear all the way to bolt failure in torqued tension. For the connection tests of Phase III, the fasteners will be expected to experience tensile loads no greater than about 45 kips for calibrated wrench installation. Consequently, strain gauges can be reliably used for these tests.

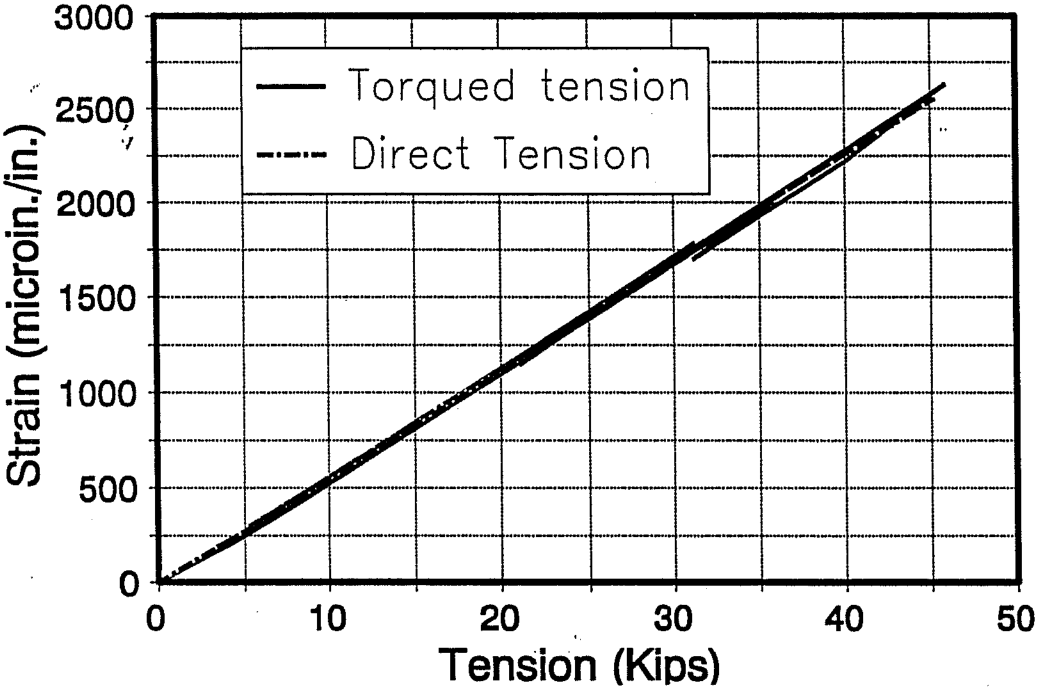


Figure 3.19: Comparison of strains: 3-1/4" conventional A325 in direct and torqued tension

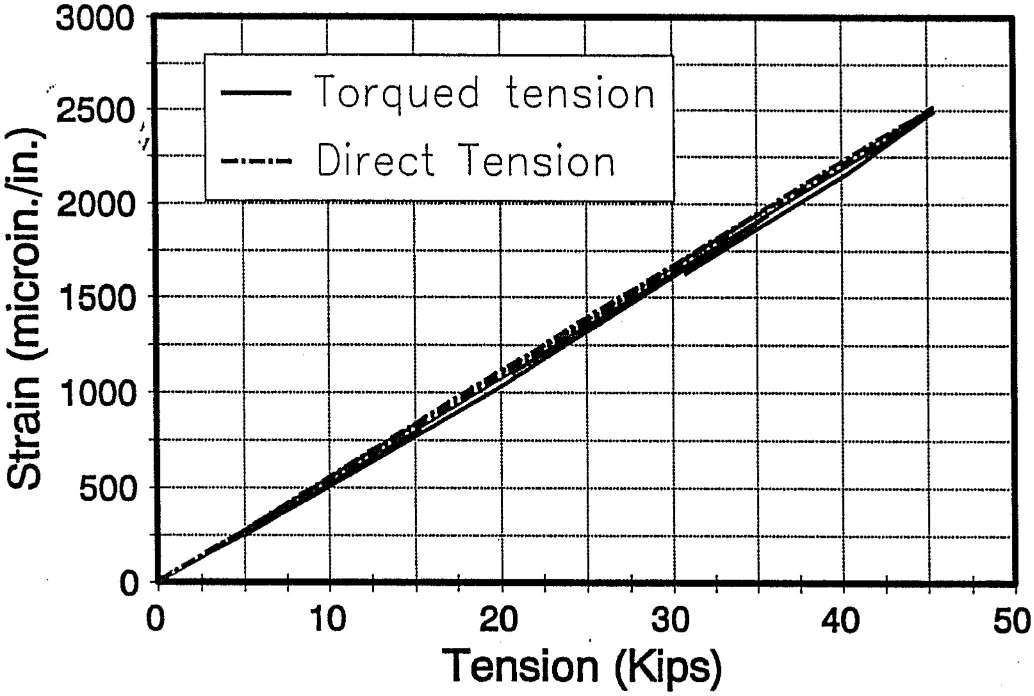


Figure 3.20: Comparison of strains: 5" conventional A325 in direct and torqued tension

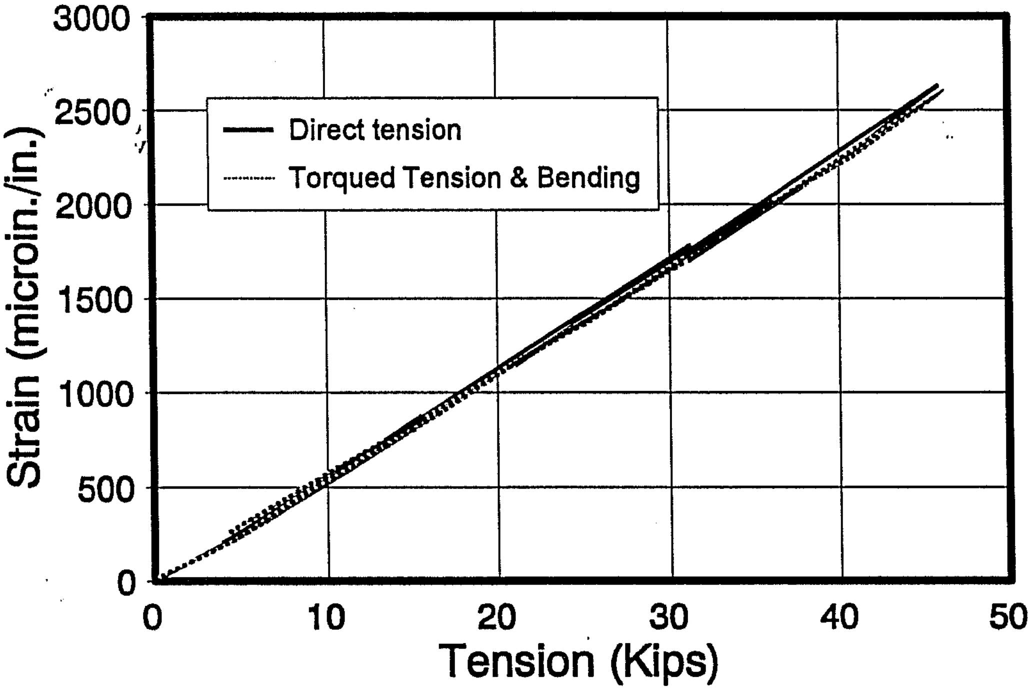


Figure 3.21: Comparison of strains: 3-1/4" A325 in direct tension & torqued tension w/bending

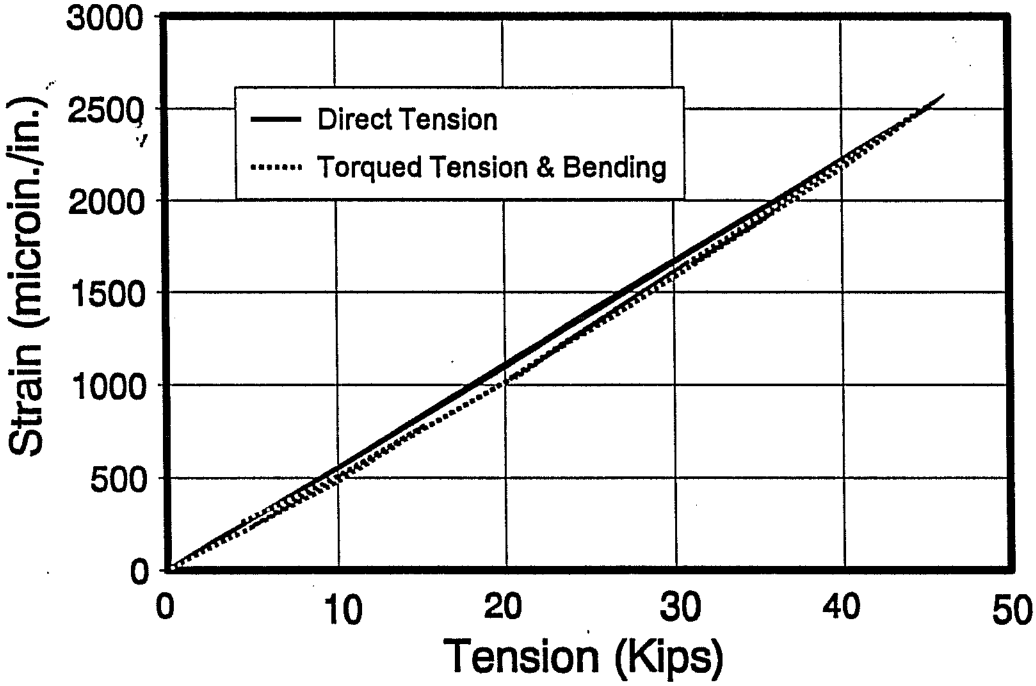


Figure 3.22: Comparison of strains: 5" A325 in direct tension & torqued tension w/bending

4.) For the galvanized bolt with a lubricated nut loaded in torqued tension, the unthreaded portion of the fastener did not stay elastic above a load of about 54 kips. This situation might appear during turn-of-nut installation where yielding may occur in the unthreaded shank. For tests using turn-of-nut, yielding in the shank will be checked by taking a final reading of gauge strains after loosening the nuts and unloading all fasteners. The presence of residual strains will indicate yielding and final bolt tensions will then have to be calculated in a special manner. If residual strains are present, they will be subtracted from the strains recorded in the bolts after the tightening of the last fastener. The net strain values will be elastic unloading strains and may be used to calculate the final tensile loads in the bolts. If no residual strains are present in the fasteners, the unthreaded shanks will be assumed to have remained elastic for the duration of the test.

5.) The shank gauges and the BTM gauge showed nearly identical performance in the evaluation/reliability tests. As noted in Section 3.1.2, the BTM gauges are preferable from the point of view of handling and installation. Consequently, the BTM gauges were chosen for strain measurement in the connection tests.

3.5 TESTS ON HUCK INTERNATIONAL C50L FASTENERS

Based on the performance of the BTM gauges in the conventional A325 tests, the decision was made to test the C50L Huck fasteners with only the BTM gauges installed. It was hoped that the BTM gauges would exhibit similar behavior when tested in the Huck fasteners. As noted previously, the size of all Huck fasteners tested was 7/8" and the grip lengths were 32 and 48.

Prior to the start of testing on the strain gauged Huck fasteners, a preliminary test was conducted to determine the tensile load at which yielding of an uninstalled Huck fastener began. This yielding would occur in the break neck of the fastener. A single, ungauged and uninstalled fastener was loaded in direct tension in the 600 kip Satec test machine. Applied load was read directly from the machine and a dial gauge was used to record movement of the machine deck. A typical tension versus elongation curve for the Huck fastener is shown in Fig. 3.23. Yielding of the fastener initiated at about 33 kips.

The tensioning of the ungauged fastener was accomplished using the Huck tensioning jig described in Section 3.4. Tensioning of the Huck fastener, however, posed a special difficulty. The fastener could not be installed in the plates of the Huck tensioning jig by swaging a collar onto

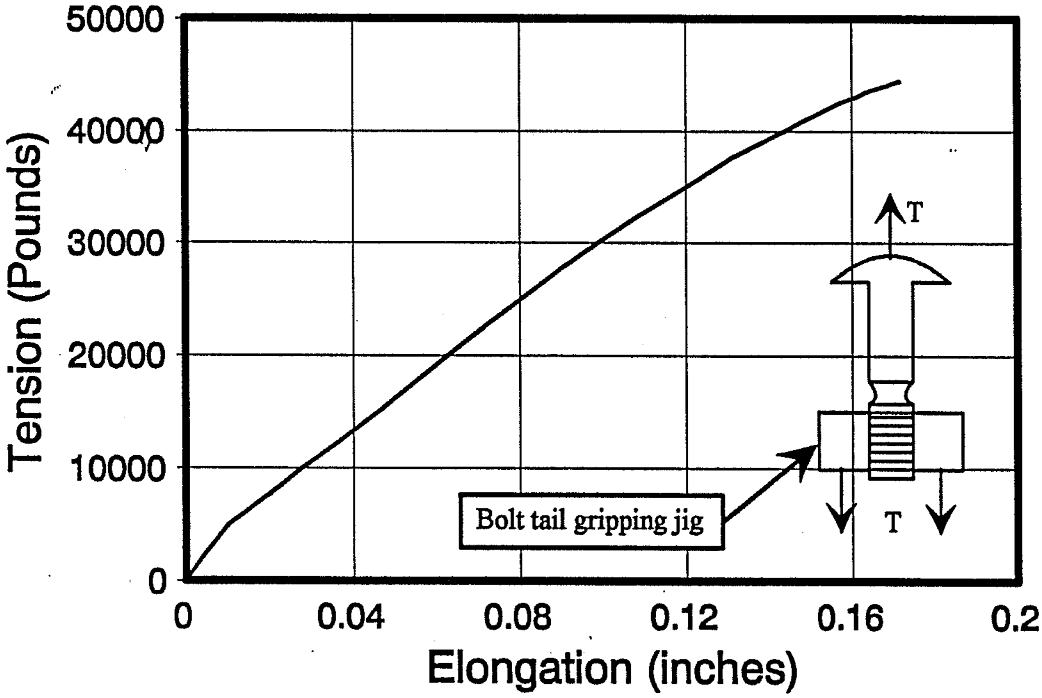


Figure 3.23: Tension vs. elongation for a typical Huck C50L fastener

the pin, since the fastener could not then be reused in the actual connection test. Consequently, a removable "nut" was needed to apply tension to the Huck fastener during the calibration process. For this purpose, a "fastener-tail gripping jig" was constructed, using a post-tensioning strand chuck typically used in post-tensioned concrete applications. The chuck had wedge grips that grabbed the tail of the Huck fastener. The wedge grips of the chuck were machined to match the groove pattern on the Huck fastener tail. This chuck is similar to the device in the head of the Huck installation tool that grabs the fastener tail during installation. A photograph of the gripping device installed on a Huck fastener is shown in Figure 3.24.

All fasteners used in the tests described in the remainder of this section were strain gauged fasteners. All strain gauge readings were monitored using the digital data acquisition system.

3.5.1 DIRECT TENSION TESTS

For these tests, two Huck fasteners of each grip length were loaded in the Satec 600 kip machine in direct tension with the use of the Huck tensioning jig (see Section 3.4) Load was monitored directly from the machine by the data acquisition system. The Huck fasteners were

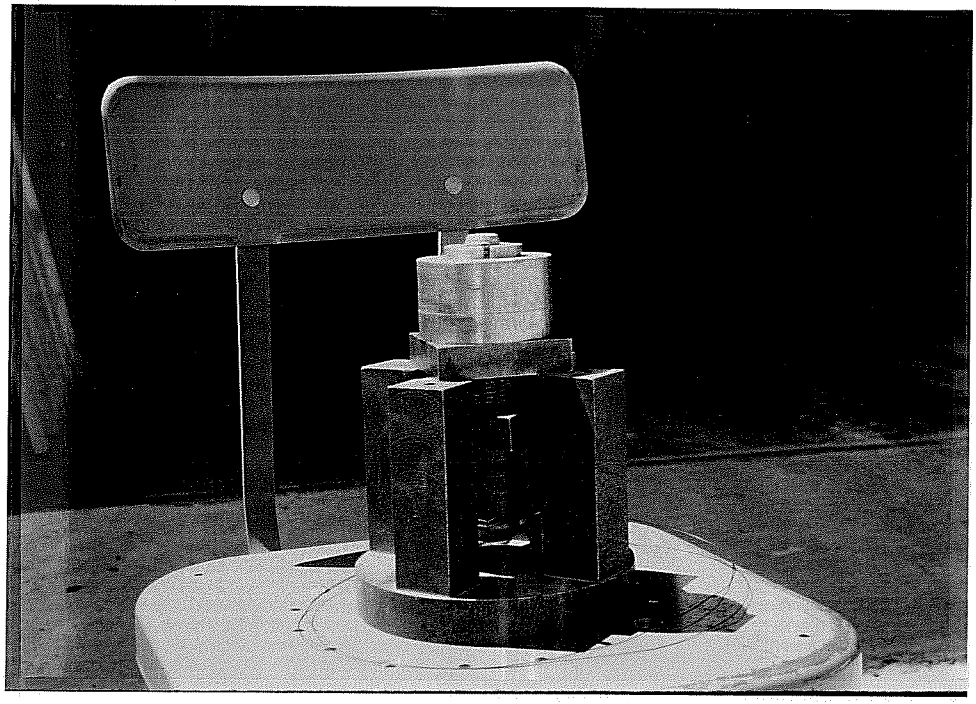


Figure 3.24: Bolt tail gripping jig installed on a Huck fastener

held in the Huck tensioning jig by the tail gripping device as described above. The fasteners were loaded to a maximum of 30 kips (to prevent break-neck yielding) and the loads were cycled during both loading and unloading.

The results of the direct tension tests are seen in Figures 3.25 through 3.28. It is readily observed that the curves of BTM gauge strain vs. load stay linear up to the 30 kip load level. Also apparent is the fact that hysteresis in the gauge output is minimal and will produce load measurement errors of less than 1 kip.

Data from the direct tension tests were entered into a spreadsheet program (Microsoft Excel) and an equation was generated for the relationship of load vs. strain for each fastener through the use of linear regression. By constraining the curve to go through the origin, the only equation parameter required is a "calibration slope" for the line which is produced by the regression. This slope can then be multiplied by the measured gauge strains to generate theoretical values of load in the particular fastener. The validity of this procedure was investigated in the remainder of the Huck fastener tests. Specifically, it was desired to know whether a calibration slope based on direct tensile loading was appropriate to predict tensile loads in installed fasteners in tension and in tension with bending.

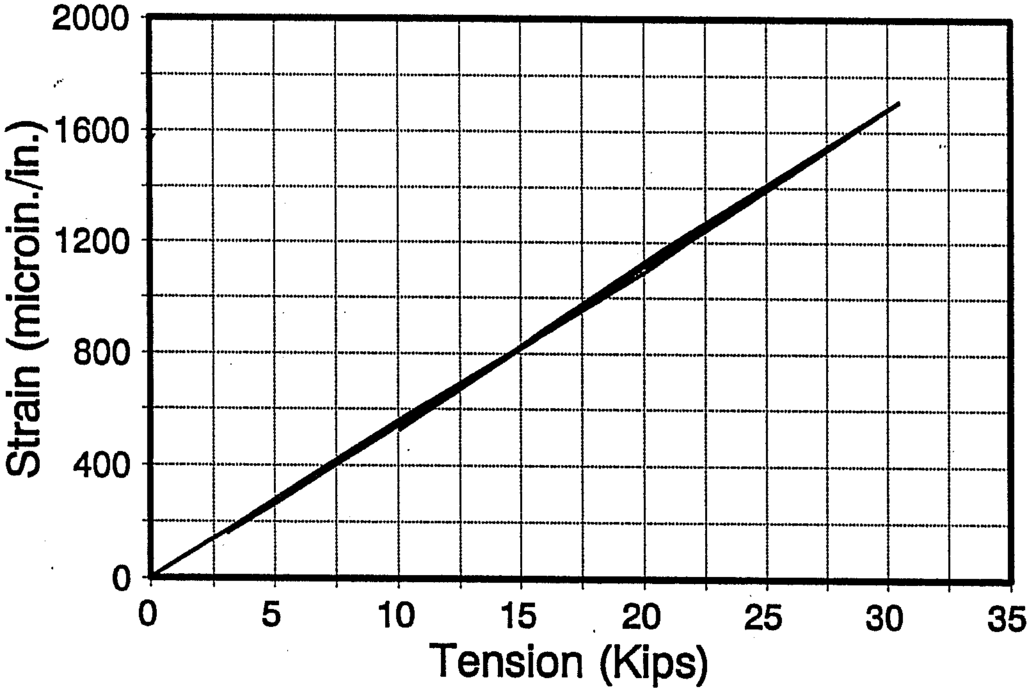


Figure 3.25: 32 grip Huck fastener #1 in direct tension - calibration curve

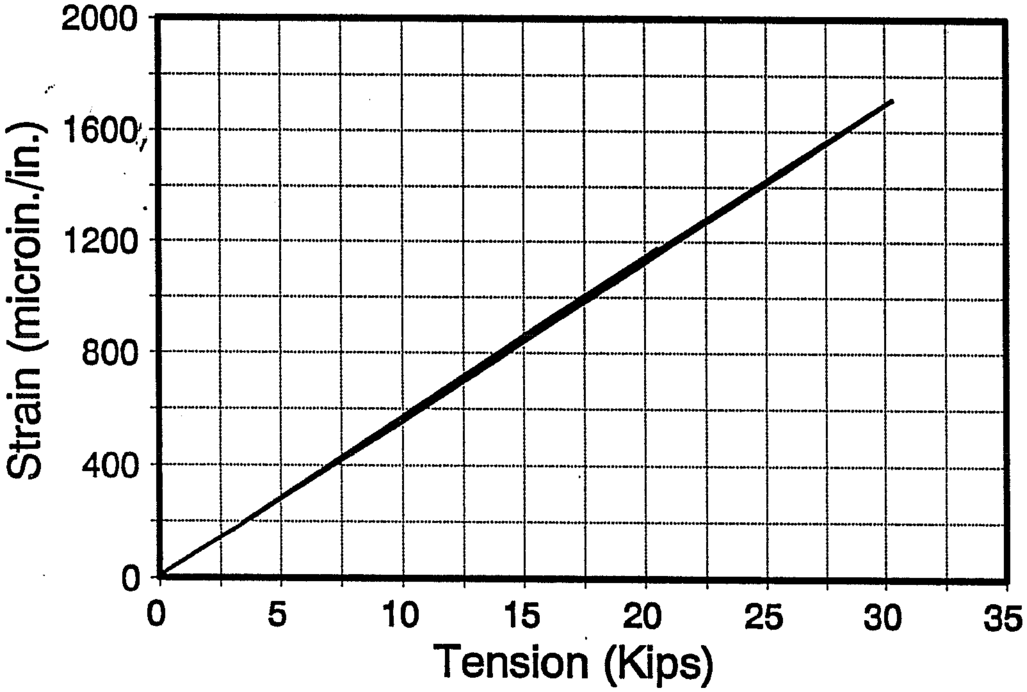


Figure 3.26: 32 grip Huck fastener #2 in direct tension - calibration curve

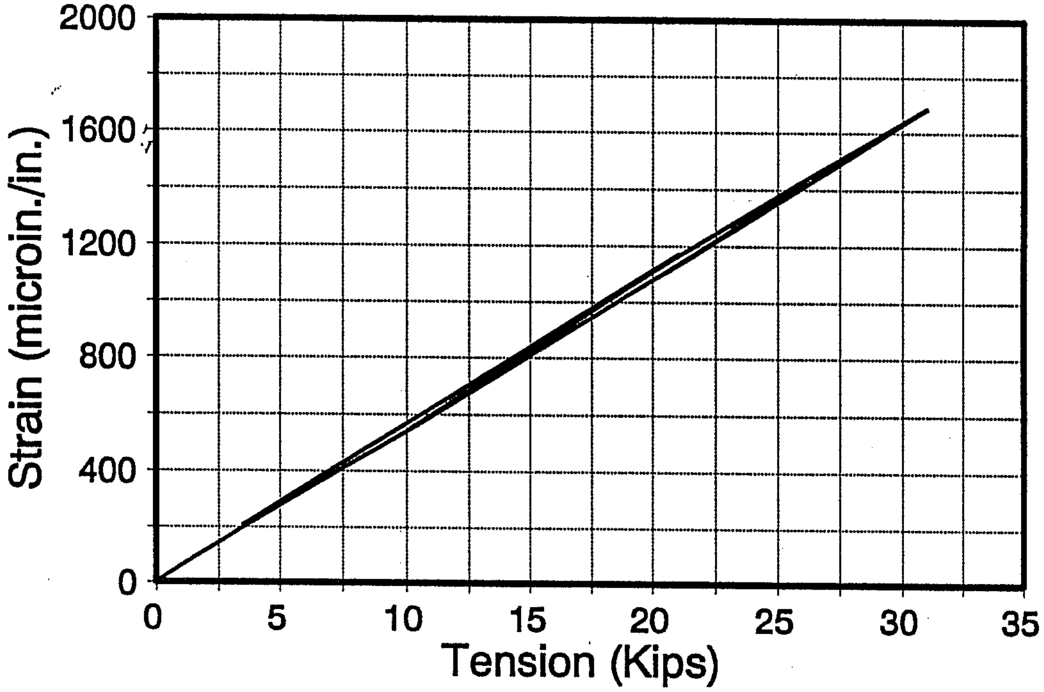


Figure 3.27: 48 grip Huck fastener #1 in direct tension - calibration curve

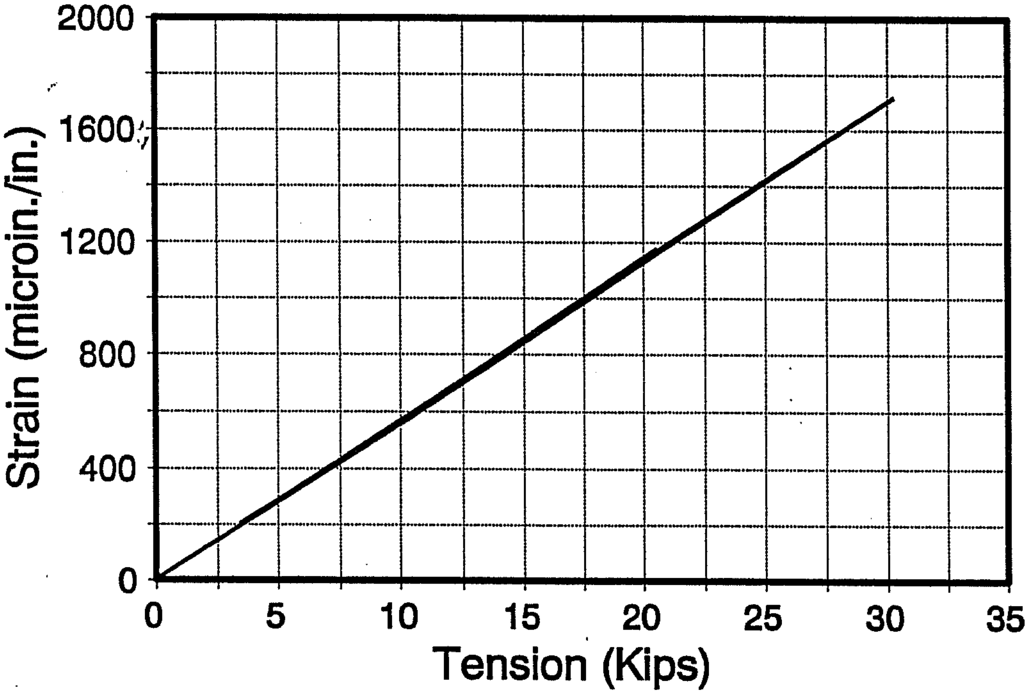


Figure 3.28: 48 grip Huck fastener #2 in direct tension - calibration curve

The direct tension tests to 30 kips were run on two different fasteners from the same production lot for each grip length. Although all tension versus strain plots were linear, the slope of the plots were slightly different. This difference is particularly apparent for the 48 grip fasteners. This difference in slopes indicates that a separate calibration slope must be generated for each individual fastener, even when all fasteners are taken from the same production lot.

3.5.2 INSTALLED FASTENERS IN DIRECT TENSION

Of the four Huck fasteners which were used in the direct tension tests of Section 3.5.1, one of each grip length was installed (through the use of the Huck installation tool) in the Skidmore-Wilhelm bolt tension indicator. The fasteners tested were denoted 32 grip #1 and 48 grip #1. Tension was measured by the use of a pressure transducer as described in Section 3.4.2. After installation, the load in the fastener was cycled by using a hydraulic hand pump which was connected to the Skidmore via the hydraulic fitting to increase and decrease the fluid pressure in the Skidmore. Both the pump and the pressure transducer were attached to the Skidmore by means of a "tee" fitting.

Figures 3.29 and 3.30 present the results of these tests. Tables 3.1 and 3.2 compare the loads measured at a given value of strain with those that were predicted by the calibration slopes for each fastener generated by the direct tension tests. The plots of BTM strain vs. load are nearly linear over the entire range of loads applied to the fastener. Hysteresis in the gauge output is negligible. Tables 3.1 and 3.2 show that the calibration slopes can predict the actual tensile load in the fasteners to an accuracy of about 1 to 1-1/4 kips for loads up to about 50 kips. For higher values of load, the accuracy drops to about 1-1/2 kips but it is not expected that loads in the fasteners will reach these levels during the actual connection tests.

3.5.3 INSTALLED FASTENERS IN DIRECT TENSION AND BENDING

These tests were identical to those of Section 3.5.2 except that a 2.86 degree beveled washer was utilized under each collar to induce bending in the Huck fasteners. The remaining Huck fastener of each length (32 grip #2 and 48 grip #2) was installed in the Skidmore with the installation tool.

The results of these tests are presented in Figures 3.31 and 3.32. Tables 3.3 and 3.4 show a comparison of measured load vs. predicted load for each fastener. As in the tests of the installed Huck fasteners without bending, these tests show a linear relationship between strain and

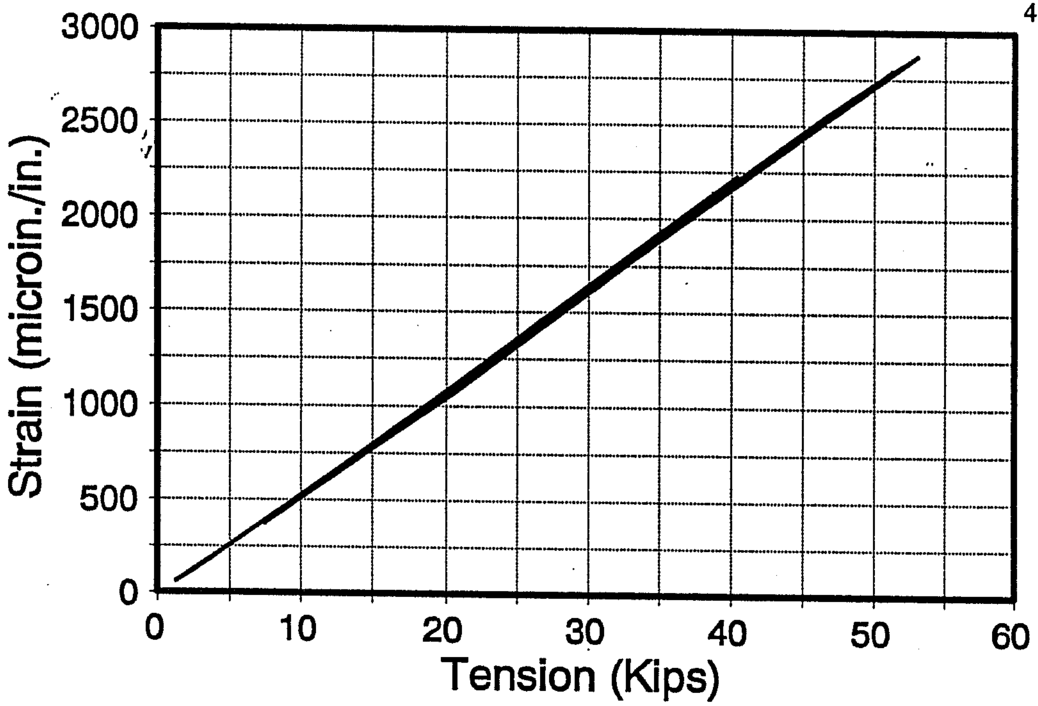


Figure 3.29: 32 grip Huck fastener #1 - installed in direct tension

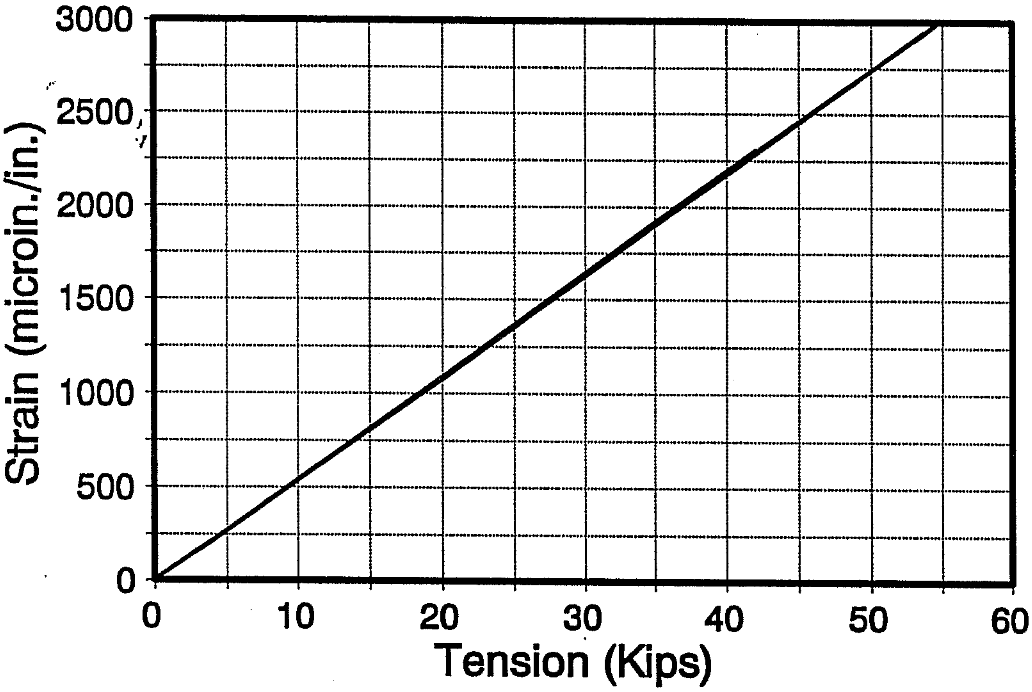


Figure 3.30: 48 grip Huck fastener #1 - installed in direct tension

Reading #	Measured Load (Kips)	Predicted Load (Kips)	Error (Kips)
1	0.04	-0.02	0.06
2	40.47	40.11	0.36
3	14.85	14.14	0.71
4	31.70	30.73	0.97
5	40.65	39.92	0.73
6	15.30	14.58	0.72
7	25.80	24.88	0.92
8	2.32	1.93	0.39
9	1.23	0.99	0.24
10	15.81	14.91	0.90
11	24.93	24.17	0.76
12	40.43	39.62	0.81
13	46.09	45.27	0.82
14	49.88	48.87	1.01
15	53.16	51.72	1.44
16	7.40	6.60	0.80
17	20.28	18.89	1.39
18	40.57	39.43	1.14
19	51.31	50.23	1.08

Average error for loads<50 kips= 0.75 kips

Average error for loads>50 kips= 1.26 kips

Table 3.1: Comparison of measured vs. predicted loads for installed 32 grip Huck fastener #1 (direct tension)

Reading #	Measured Load (Kips)	Predicted Load (Kips)	Error (Kips)
1	0.05	-0.02	0.06
2	42.11	42.25	0.14
3	13.25	13.02	0.23
4	22.67	22.38	0.29
5	32.78	32.49	0.30
6	39.77	39.57	0.20
7	49.34	49.20	0.14
8	12.60	12.33	0.27
9	30.13	29.79	0.34
10	11.25	10.99	0.26
11	2.55	2.44	0.11
12	19.69	19.26	0.43
13	27.42	27.09	0.33
14	40.73	40.49	0.24
15	48.70	48.60	0.10
16	53.45	53.58	0.13
17	53.39	53.35	0.04
18	54.64	54.63	0.01
19	25.28	25.14	0.14
20	38.78	38.54	0.24
21	9.82	9.61	0.21
22	2.81	2.71	0.10
23	41.07	40.85	0.22
24	18.61	18.37	0.24
25	11.65	11.41	0.24

Average error for loads<50 kips= 0.22 kips

Average error for loads>50 kips= 0.06 kips

Table 3.2: Comparison of measured vs. predicted loads for installed 48 grip Huck fastener #1 (direct tension)

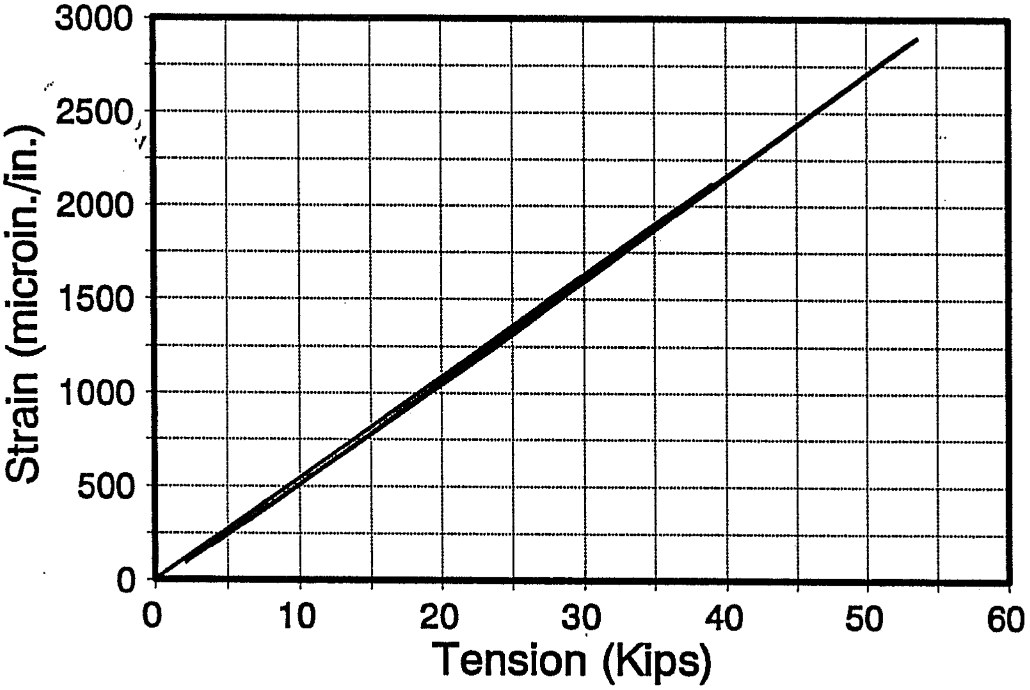


Figure 3.31: 32 grip Huck fastener #2 - installed in direct tension & bending

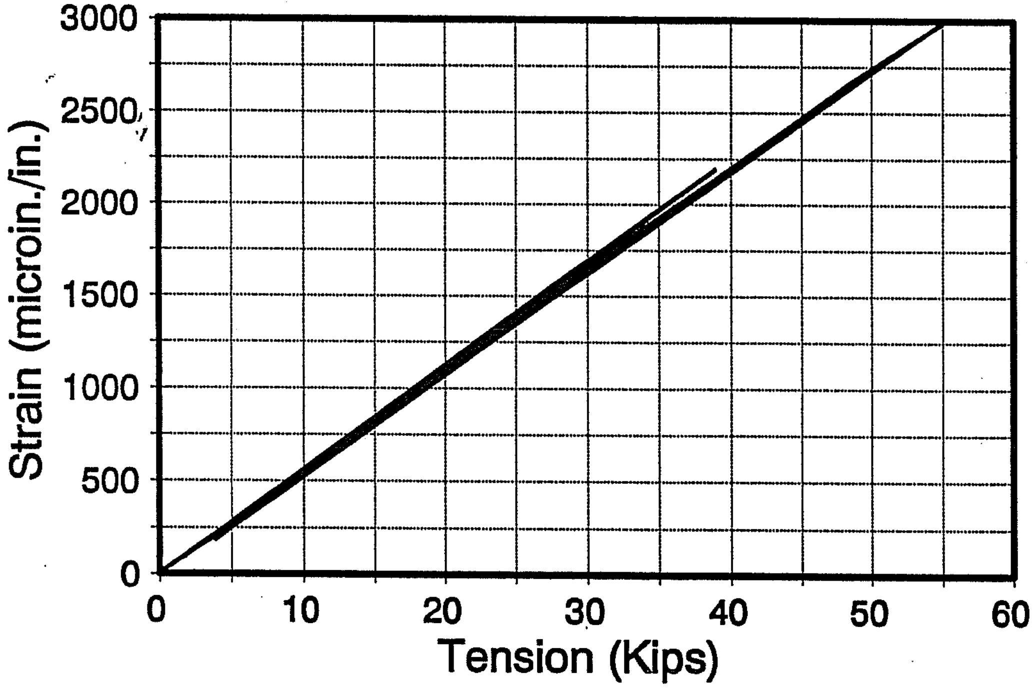


Figure 3.32: 48 grip Huck fastener #2 - installed in direct tension & bending

Reading #	Measured Load (Kips)	Predicted Load (Kips)	Error (Kips)
1	0.05	0.00	0.05
2	39.10	37.35	1.75
3	16.41	14.97	1.44
4	27.06	25.48	1.58
5	40.08	38.11	1.97
6	48.42	46.20	2.22
7	17.78	16.39	1.39
8	37.88	35.87	2.01
9	52.04	49.67	2.37
10	16.59	15.28	1.31
11	8.81	7.66	1.15
12	3.92	3.13	0.79
13	24.68	22.72	1.96
14	41.15	38.96	2.19
15	52.70	50.27	2.43
16	53.72	51.14	2.58
17	28.07	26.42	1.65
18	14.65	13.40	1.25
19	8.25	7.30	0.95
20	2.13	1.58	0.55

Average error for loads<50 kips= 1.42 kips

Average error for loads>50 kips= 2.46 kips

Table 3.3: Comparison of measured vs. predicted loads for installed 32 grip Huck fastener #2 (direct tension and bending)

Reading #	Measured Load (Kips)	Predicted Load (Kips)	Error (Kips)
1	0.04	0.00	0.04
2	39.01	38.73	0.28
3	20.67	19.97	0.70
4	33.34	32.11	1.23
5	45.10	43.68	1.42
6	23.82	23.29	0.53
7	12.21	11.58	0.63
8	32.08	30.67	1.41
9	41.08	39.64	1.44
10	20.65	20.27	0.38
11	29.41	28.12	1.29
12	7.89	7.07	0.82
13	2.53	2.29	0.24
14	24.91	23.70	1.21
15	33.59	32.23	1.36
16	42.62	41.26	1.36
17	48.52	46.98	1.54
18	53.24	51.08	2.16
19	54.73	52.30	2.43
20	55.21	52.92	2.29
21	16.93	16.11	0.82
22	3.82	3.19	0.62
23	32.04	30.47	1.57
24	40.64	38.95	1.69
25	1.67	1.54	0.13

Average error for loads<50 kips= 0.94 kips

Average error for loads>50 kips= 2.29 kips

Table 3.4: Comparison of measured vs. predicted loads for installed 48 grip Huck fastener #2 (direct tension and bending)

load for load values up to about 55 kips. Hysteresis in the gauge output is more prevalent than in the results of Section 3.5.2. Tables 3.3 and 3.4 indicate that the introduction of bending into the fasteners increases the maximum error in load measurement by the BTM gauges to almost 2 kips. As in the results of Section 3.5.2, higher errors of predicted load (by the BTM gauges) occur at values of load well above those anticipated in the Huck fasteners during the connection tests of Phase III.

3.5.4 CONCLUSIONS OF THE HUCK FASTENER TESTS

The tests performed on the Huck fasteners instrumented with the BTM strain gauges produced several important conclusions. They are summarized as follows:

1.) For the uninstalled Huck fasteners loaded in direct tension, the relationship of strain vs. applied load is linear up to the 30 kip limit imposed to prevent break-neck yielding. When installed in the Skidmore, the behavior of the same fasteners is linear to values of load that exceed 55 kips.

2.) The cycling of loads in the fasteners, both installed and uninstalled, results in minimal hysteresis effects in the strain gauge output. The maximum expected error due to any hysteresis effects is less than 1 kip. The BTM gauges, then, can be used to accurately measure tension in the Huck fasteners, even when subjected to varying tensile loads during installation.

3.) The effects of bending upon strain gauge output are minimal. When installed in the Skidmore with a beveled washer to induce bending (Section 3.5.3), little deviation from linear response to applied load is noted in the BTM gauge output. As the beveled washers used duplicate the conditions to be expected in out-of-flat plates, it can be concluded that fastener bending resulting from deformed plates will not affect strain gauge readings.

4.) Calibration slopes derived from direct tension tests will accurately predict tensile load for Huck fasteners after installation. Based on the results of the tests, it is concluded that calculated loads based on the calibration slopes are within 2 kips of the actual measured loads, regardless of the loading conditions imposed on the fastener.

3.6 CONCLUSIONS OF THE EVALUATION/RELIABILITY TESTS

From the results of the conventional A325 and Huck C50L evaluation/reliability tests, the following overall conclusions can be made:

1.) Both the surface strain gauges and the BTM bolt gauges provide accurate, repeatable values of strain at a given load under a variety of anticipated loading conditions including bending, torsion, and cycled loads.

2.) The BTM gauges can measure the tensile load in a conventional A325 fastener to within 2 kips of the actual value, even under the worst combination of applied torsion and bending.

3.) The BTM gauges can measure the tensile load in an installed Huck C50L fastener to an accuracy of 2 kips under the worst anticipated bending conditions. For situations in which bending is not present, the maximum error is less.

4.) The BTM gauges will be used to measure fastener tensions in the connection tests of Phase III based on their ease of installation, durability, and accuracy.

5.) Each fastener (both Huck and conventional A325) will be calibrated prior to installation to derive a calibration slope for the strain vs. load relationship of the fastener. Huck fasteners will be loaded in direct tension to approximately 30 kips. Conventional A325 bolts will be loaded in direct tension to about 40 kips. It is apparent that for load values in these low ranges, the curves of load vs. strain are relatively linear in both types of fasteners. Due to this inherent linearity, only a small number of calibration readings of strain and tensile load (six or eight) will be taken for each fastener. These readings will be taken during both loading and unloading to provide an accurate calibration curve. Calibration slopes will be generated using the linear regression capabilities of the Excel spreadsheet package as was done for the direct tension tests of Section 3.5.1. The test procedure used in Section 3.5.1 is the model for all future fastener calibrations. All calibrations will be conducted in the Satec 600 kip testing machine with the Huck tensioning jig (Figure 3.3) used to induce tension in the fasteners.

CHAPTER 4

CONNECTION TESTS WITH CONVENTIONAL A325 FASTENERS

4.1 GENERAL

Conventional A325 bolts were used as the fasteners in the initial connection tests of Phase III. The connections in which the fasteners were installed were three plate lap splices with a thick interior plate and thinner exterior plies.

All fasteners used in the tests reported in this chapter were 7/8" diameter with lengths of 3-1/4", 4-1/4", and 5-1/4" for the 2", 3", and 4" grips, respectively. The fasteners were specified to be in accordance with ASTM A325-93, the nuts in accordance with ASTM A563 Grade DH, and the washers in accordance with ASTM F436. All components were specified to be mechanically galvanized. In addition, all fastener assemblies were specified to be in accordance with the Federal Highway Administration "Supplemental Contract Specifications for Projects with AASHTO M164 (ASTM A325) High-Strength Bolts", dated November 1989. Test reports provided by the bolt supplier indicated that all fastener components were in compliance with all of these specifications. Additionally, selected tests to verify compliance with these specifications were conducted upon receipt of the bolts. These included ultimate strength tests, Rockwell hardness tests, and rotational capacity tests. The details and results of these tests are detailed in Appendix A at the back of this report. BTM bolt strain gauges were installed in each bolt, and each bolt was calibrated as described in Chapter 3. All BTM strain readings were monitored and recorded by the digital data acquisition system.

The conventional fasteners used for these tests were different than those used in the evaluation/reliability tests described in Chapter 3. In those tests, the fasteners were non-galvanized while the fasteners used in the tests described hereafter were mechanically galvanized. The decision was made to use galvanized conventional A325 bolts in the actual connection tests subsequent to the Huck International request to use galvanized Huck fasteners in the connection tests using the LPC fasteners (Chapter 5).

Figure 4.1 presents a diagram of a typical joint in the testing program. The plates used in the connections were all of ASTM A572 Grade 50 steel. As noted in Figure 4.1, the outer plates were one-half the thickness of the inner plate. Total grip lengths investigated were 2", 3", and 4" which correspond to middle plate thicknesses of 1", 1-1/2", and 2" and outer plate thicknesses of 1/2", 3/4", and 1", respectively. All holes were drilled to a diameter of 15/16".

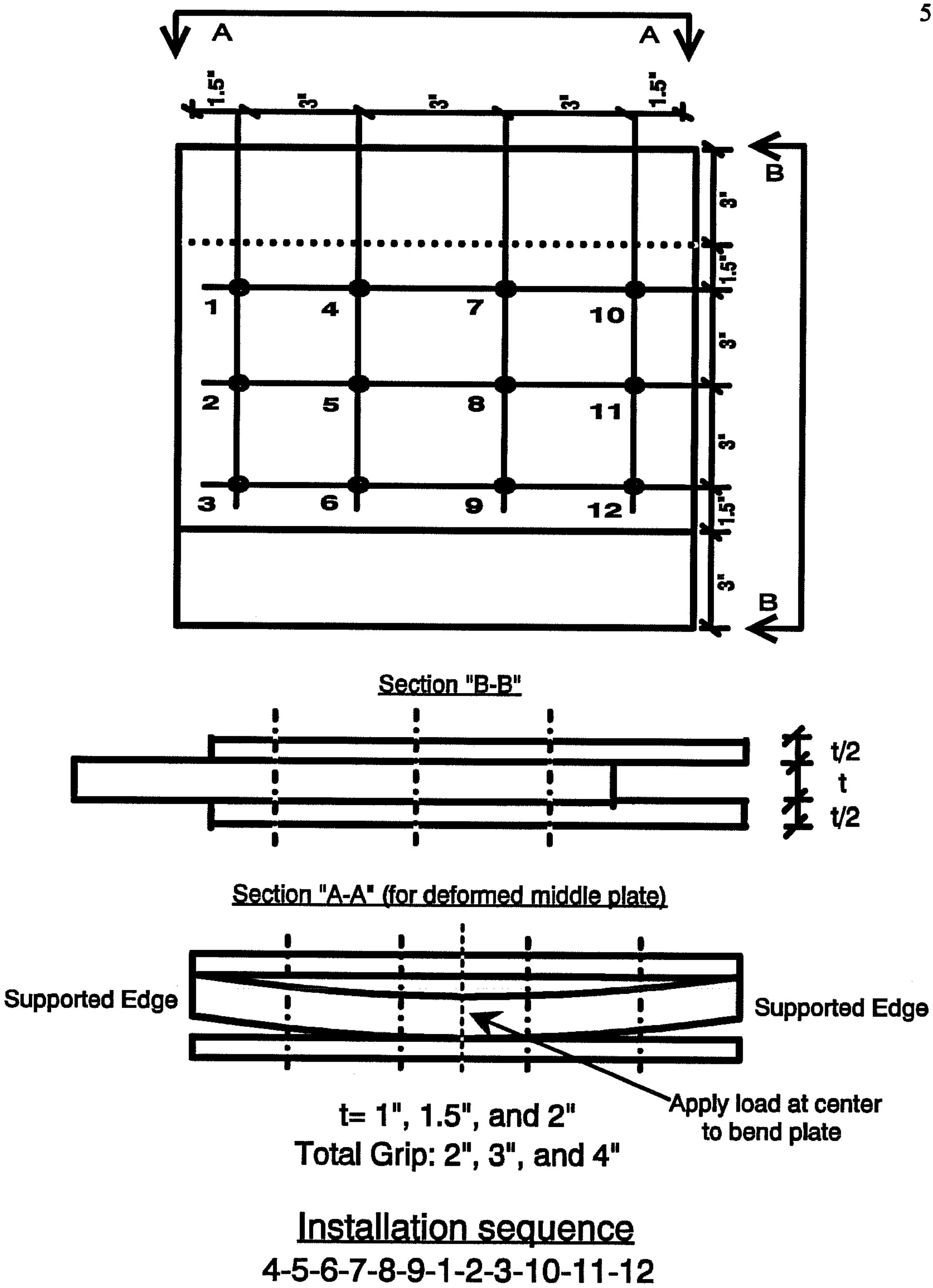


Figure 4.1: Plate layout and orientation for connection tests

Tests were conducted with the plates in two different conditions: flat and deformed. For the flat plate tests, the fasteners were installed with all plates in their nominally flat, as-delivered condition. For the deformed plate tests, the center plate was bent in single curvature, to a deflection of 3mm (Figure 4.1), with the outer plates remaining nominally flat. The deformation pattern and magnitude was chosen somewhat arbitrarily based on the judgement of the investigators as to what constitutes a plausible out-of-flat condition. In the literature search conducted for this project, no information was found on actual out-of-flatness measurements for structural steel connections. Thus, there appears to be no quantitative data available on the actual out-of-flatness conditions that can be expected in the field. ASTM A6 specifies permissible variations from flatness for rectangular steel plates, as received from the steel mill. The permissible variations vary depending on the width, length, and thickness of the plate, as well as on the grade of steel. For all plates used in this investigation, the ASTM A6 specified permissible variation from flatness is 3/8" (9.5mm). Consequently, the 3mm deformation used in these tests is well below specification limits.

The 3mm plate deformation was produced by cold bending the middle plates using the 600 kip test machine. Each plate was simply supported along opposite edges and loaded in the center of the plate. The supports and load ran the entire length of the plate, in the direction opposite of the induced curvature (see Figure 4.1). Due to the nature of the bending operation, and the residual plastic deformations at the center of the plates, the middle plates appeared to have been deformed into a shape resembling an "V" (i.e. a relatively sharp bend in the middle, rather than a uniform, smooth curvature).

A photograph of an actual test set-up can be seen in Figure 4.2. The plates of the splice were prevented from rotating by the steel blocks which are firmly clamped to the test fixture. The entire fixture was clamped to a structural column in the laboratory. Rotation of the bolt heads was precluded by steel bars which ran between the rows of bolt heads on the underside of the test fixture. Figure 4.3 shows a photograph of this arrangement. The plates were not secured to the test fixture, nor were they prevented from deforming installation.

The conventional A325 tests sought to investigate the effects of several variables on the tensions of the fasteners at both the snug tight and fully tightened conditions. These variables are summarized as follows:

Length of grip: 2", 3", or 4" total splice thickness

Method of installation: Calibrated wrench with no snugging

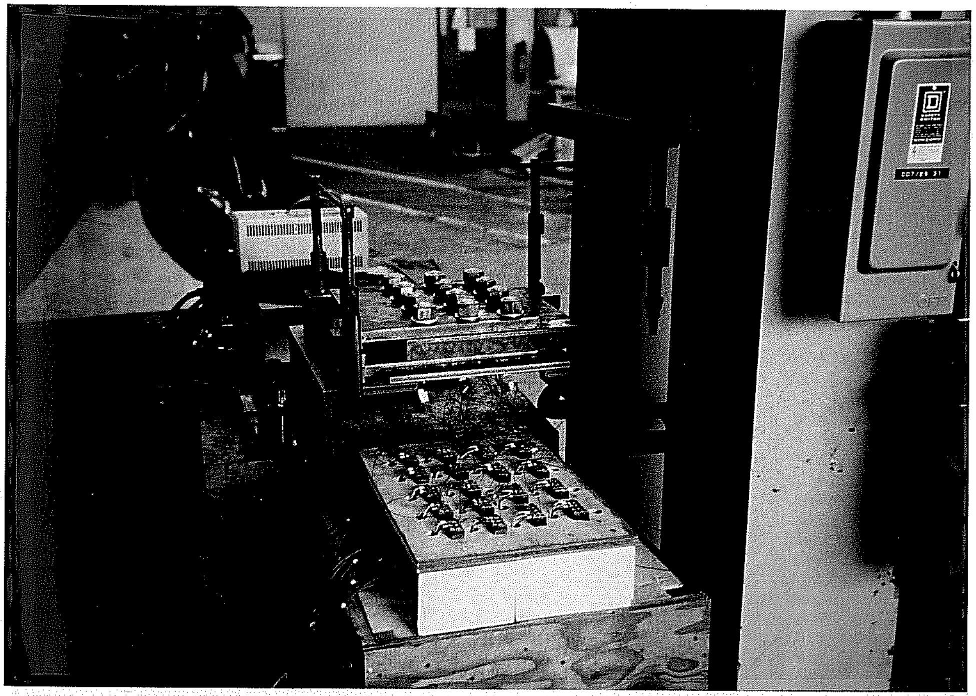


Figure 4.2: Typical conventional A325 connection test set-up

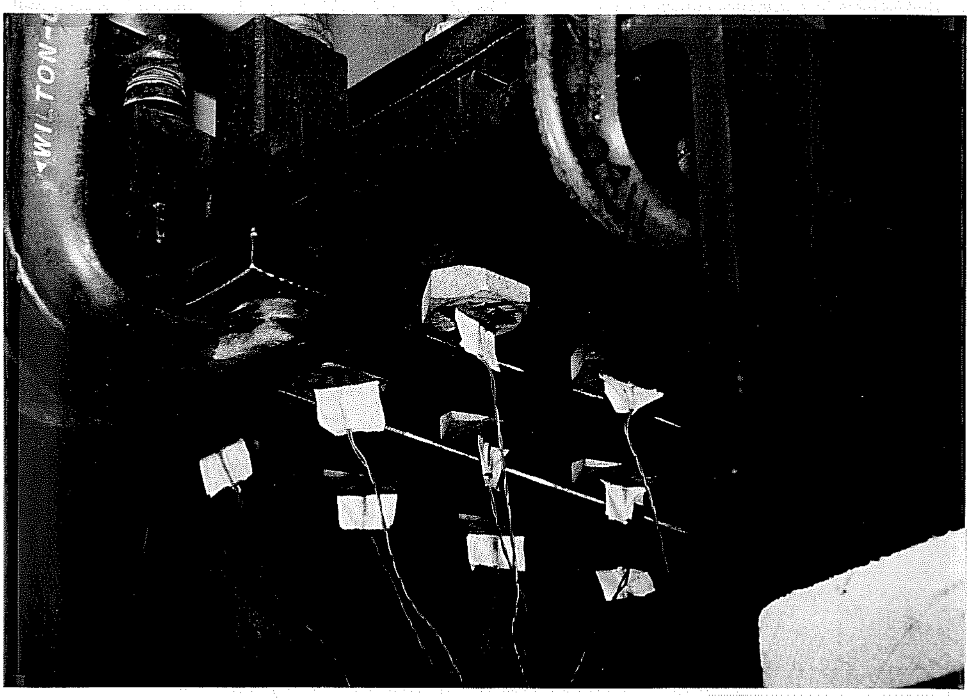


Figure 4.3: Conventional A325 bolt head restraining bars

Calibrated wrench with snugging
Turn-of-Nut

Deformation of plates: Nominally flat or middle plate in singular curvature bending with mid-span deflection of 3mm

The condition of each variable was altered from test to test so that each connection tested was a unique combination of the three individual variables.

To conveniently record and index the results of the conventional A325 fastener tests a special system is used to name each individual test. Each test is described according to the type of fastener used, the flatness condition of the test plates, the method of fastener installation, and the thickness of the test grip. The syntax of the system is as follows:

1st Letter: Type of fastener
    C: Conventional fasteners (uniform for this chapter)
2nd Letter: Plate flatness condition
    F: Flat plates
    D: Deformed interior plate
Succeeding Letters: Method of fastener installation
    CWNS: Calibrated wrench with no snugging
    CW: Calibrated wrench with snugging
    TON: Turn-of-nut
Numerical suffix: Grip thickness
    -2: 2" grip
    -3: 3" grip
    -4: 4" grip

For example, test CFCWNS-3 features conventional fasteners installed in flat plates (3" grip) by the calibrated wrench method with no snugging. Test CDTON-2 investigates conventional fasteners in a 2" grip connection with a deformed middle plate. The installation method is turn-of-nut. A discussion of these tests and the presentation of their results comprises the balance of this chapter.

For all tests performed with the conventional A325 fasteners, a consistent order of installation of the bolts in the test connections was followed. Figure 4.1 shows a schematic diagram of the fastener layout for all connection tests. The order of fastener installation followed the *Bolt Specification* requirement that "tightening shall progress from the most rigid part of the joint to its free edges" [1]. Thus, the first row to be installed (snugged or tightened) consisted of fasteners 4, 5 and 6 while the second row contained 7, 8, and 9. The last fasteners to be installed were the rows consisting of fasteners 1, 2, and 3, and 10, 11, and 12, respectively.

4.2 FLAT PLATE TESTS

These tests were performed on the plates in their as-delivered condition from the local fabricator. Appendix B details the method by which the relative flatness of the specimens was verified. The plates were all quite flat in their as-delivered condition with typical maximum deviations in flatness of less than 0.02 inches per plate. The flat plate tests were performed on all three grip lengths and the fasteners were installed using both the calibrated wrench (with no snugging) and turn-of-nut methods.

4.2.1 CALIBRATED WRENCH (w/o SNUG) INSTALLATION METHOD

In order to get a comparison between the installed tensions of the conventional A325 fasteners and the Huck fasteners, a modified calibrated wrench installation method was utilized. To simulate the single pass installation (see Chapter 2) of the Huck fasteners, the conventional A325 bolts were tightened directly to the 39 kip minimum preload without first being snugged. The target load was 5% above 39 kips, or about 41 kips per the *Bolt Specification* [1] for calibrated wrench installation. Load control was accomplished with a torque wrench and a known torque-load relationship. This relationship was derived in the A325 verification tests performed on the conventional fasteners upon their receipt (see Appendix A). Prior to each test, sample fasteners (new bolts with new nuts and washers) were installed in the Skidmore-Wilhelm bolt tension indicator to verify the adequacy of the torque indicated by the verification tests to develop the 41 kip load in the fasteners. Torque settings on the wrench had to be changed for some tests, but all were in the range of 280-300 ft*# to achieve 41 kips in the Skidmore. Figure 4.4 illustrates the use of a torque wrench to install conventional A325 fasteners by the calibrated wrench method.

The results of these tests are reported under the CFCWNS series designation.

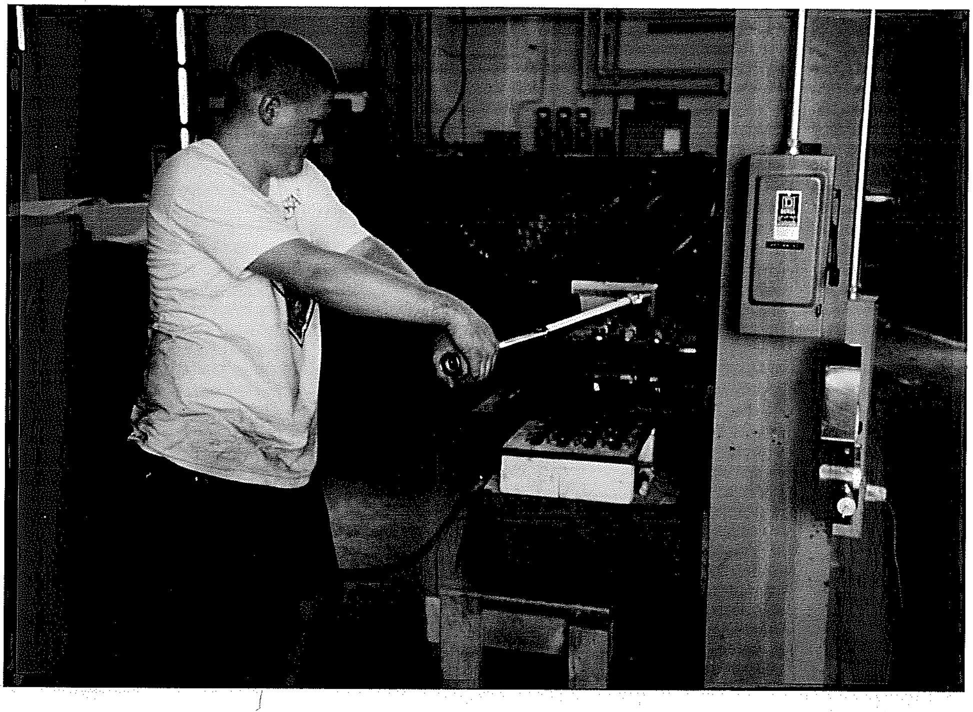


Figure 4.4: Installation of a conventional A325 fastener with a torque wrench

4.2.1.1 TEST RESULTS

The presentation of results for the calibrated wrench tests, as well as for all of the conventional A325 fastener tests, follows the same format. For each test, five figures are presented to detail the observed results. The first is a chart showing the tensions measured in each fastener during the progressive installation of the fasteners. From this chart, the load history of each individual bolt can be derived. The second figure is a vertical bar chart indicating the final installed tensions in each bolt and their relationship to the 39 kip minimum preload for a 7/8" diameter A325 fastener. The final three figures are graphical representations of the load histories of three individual fasteners, 4, 8, and 2, in the connections. Each fastener is from a different row in the connection and is chosen as representative of fastener behavior in that part of the connection.

Table 4.1 presents a summary of the pertinent fastener tension results of the CFCWNS series tests. Included in this table are the average values of final fastener tension, initial fastener tension, and fastener tension loss during the installation sequence. The final tensions refer to those recorded in the fasteners upon the tightening of the last bolt in the connection (12). Initial fastener tensions are those measured in each bolt immediately after tightening of that particular fastener. Tension loss indicates the drop in fastener tensile load between the initial installation of the individual bolt and the final tightening of the last fastener in the connection. Standard deviations for each quantity are also listed in order to provide a representation of the scatter in the various data sets.

Test CFCWNS-2:

Figures 4.5 through 4.9 and Table 4.1 present the results of this connection test. As can be seen in Figure 4.5 and Table 4.1, the average final fastener tension was 39.3 kips which is slightly above the 39 kip minimum specified preload. Tensile load in the fasteners changed very slightly upon the tightening of subsequent bolts. Table 4.1 shows that the average loss was only 0.3 kips of tension. Figures 4.7 to 4.9 show this trend graphically for fasteners 4, 8, and 2 which are representative of fasteners in both the interior and exterior regions of the connection. Table 4.1 indicates that the average value of tension initially induced in each fastener was 39.6 kips with a standard deviation of about 1.2 kips. The maximum variation in individual initial fastener loads was 4.1 kips as shown in Figure 4.5.

Test CFCWNS-3:

The results of this test are presented in Figures 4.10 to 4.14 and in Table 4.1. The average final installed fastener tension for this test was 40.9 kips, almost 2 kips above the 39 kip benchmark value. As in test CFCWNS-2, little deviation in installed tensile load was noted for any bolt during the test. Table 4.1 indicates that the average loss of load in the fasteners during installation was about 0.5 kips. Figures 4.12, 4.13, and 4.14 show graphically the relatively constant levels of installed tension in bolts 4, 8, and 2. For this test, the calibrated torque wrench produced considerable variation in the tensions of the connection fasteners. The 2.7 kip standard deviation from the 41.4 kip mean value of initial tension (Table 4.1) indicates a wide range of initial installed tensions. The maximum variation in the initial installed tensions was 9 kips, as listed in Figure 4.10.

Test CFCWNS-4:

Figures 4.15 to 4.19 and Table 4.1 show the results of test CFCWNS-4. The 42.0 kip average final fastener tension (Figure 4.15) was well above the specified 39 kip minimum. As with the 2" and 3" grip tests, the tensile loads in the connection fasteners varied little during installation; the average tensile load loss for the fasteners was 1.5 kips as shown in Table 4.1. Figures 4.17, 4.18, and 4.19 illustrate the lack of tensile load variation in fasteners 4, 8, and 2. As in test CFCWNS-3, the initial loads induced in the fasteners by the calibrated wrench were quite variable.

Test #	Average Final Fastener Tension	Standard Deviation	Average Initial Fastener Tension	Standard Deviation	Average Fastener Tension Loss	Standard Deviation
CFCWNS-2	39.3	1.1	39.6	1.2	0.3	0.6
CFCWNS-3	40.9	2.5	41.4	2.7	0.5	0.8
CFCWNS-4	42.0	2.1	43.3	2.3	1.5	0.3

Note: All values in Kips

Table 4.1: Summary of fastener load results for CFCWNS series tests

Table 4.1 shows that the standard deviation in the initial loads was 2.1 kips, and the maximum variation in the initial installed tensions, as shown in Figure 4.15, was 7.7 kips.

4.2.2 TURN-OF-NUT INSTALLATION METHOD

These tests were conducted using the *Bolt Specification* [1] guidelines for turn-of-nut installation. Snugging was accomplished using a spud wrench and by following the criterion that the wrench be used with the full effort of the installer. The author performed all snugging on the fasteners in these tests in an attempt to provide a uniform snug condition. The degree of rotation of each nut past snug tight for final tightening was applied as indicated by the *Bolt Specification* and the values were as follows:

3-1/4" fastener (2" grip): 1/3 additional turn
4-1/4" fastener (3" grip): 1/2 additional turn
5-1/4" fastener (4" grip): 1/2 additional turn

The additional rotation of the nuts past snug tight was accomplished using a torque wrench and a 4X torque multiplier. A photograph of this arrangement is shown in Figure 4.20. The use of an impact wrench for this operation was precluded by concerns about the effect of the

Fastener Number

Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	38.8	0	0.3	0	0.1	0	-0	0	0	0.0	0	0.2
5.0	38.7	38.9	-0.1	0	-0	-0	-0	0.0	-0	0.0	0	0.3
6.0	38.4	39.0	40.6	0.0	-0	-0	-0	0.1	0.0	0.1	0.2	-0
7.0	38.8	38.9	40.0	38.6	-0.1	-0	-0	0.1	-0	-0	-0	-0.1
8.0	38.7	39.2	40.0	38.6	39.7	0	-0	0.1	0	0.0	-0	-0
9.0	38.7	39.2	40.1	38.4	39.5	40.3	-0	0.1	-0	-0	-0	-0
1.0	39.2	39.5	40.0	38.1	39.3	39.5	38.5	0.1	0.0	-0	-0	-0
2.0	39.2	40.2	40.1	38.0	39.2	39.4	38.4	38.5	0.1	-0	-0	-0
3.0	39.1	40.2	40.4	37.9	39.1	39.3	38.3	38.2	40.6	0	-0	-0.1
10.0	39.0	40.1	40.3	38.3	39.3	39.2	38.1	37.9	39.7	41.9	0.1	0.1
11.0	39.0	40.1	40.3	38.3	39.7	39.3	38.1	37.9	39.5	41.3	41.1	-0
12.0	39.0	40.1	40.3	38.3	39.7	39.7	38.1	37.9	39.5	41.1	40.8	37.8

Tension in Kips

Average Fastener Tension = 39.3 Kips

3-1/4" Conventional Fasteners
2" Grip
Flat Plates
Cal. Wrench Installation
(w/o Snugging)

1	4	7	10
2	5	8	11
3	6	9	12

Fastener Numbers

Figure 4.5: Fastener Tensions for Test CFCWNS-2

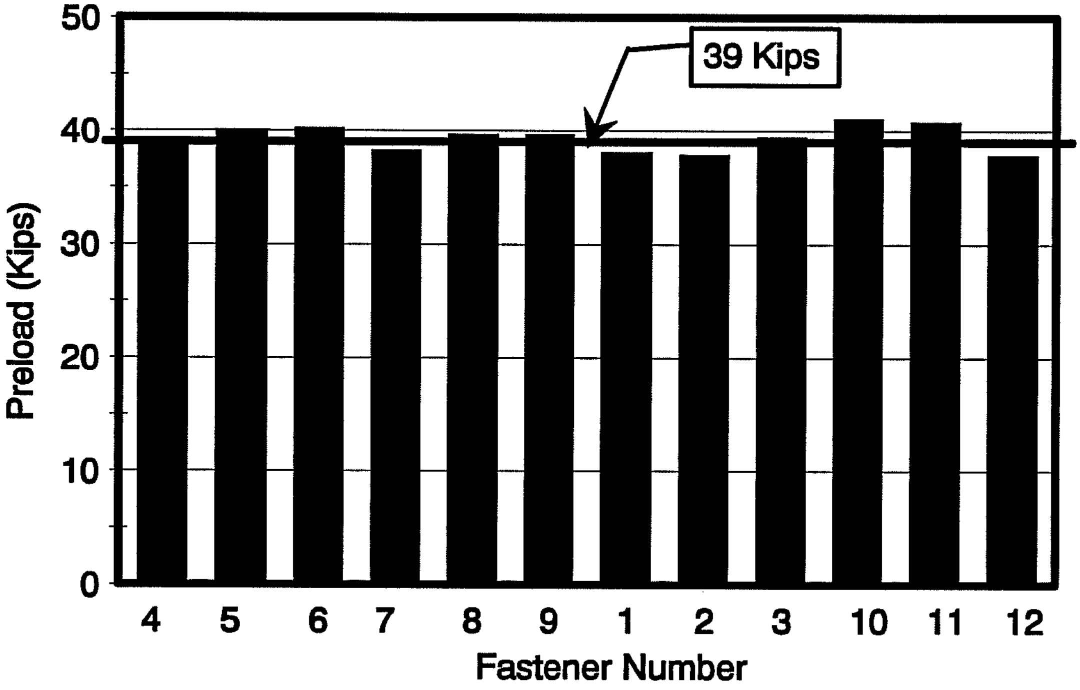


Figure 4.6: Final Installed Tensions for Test CFCWNS-2

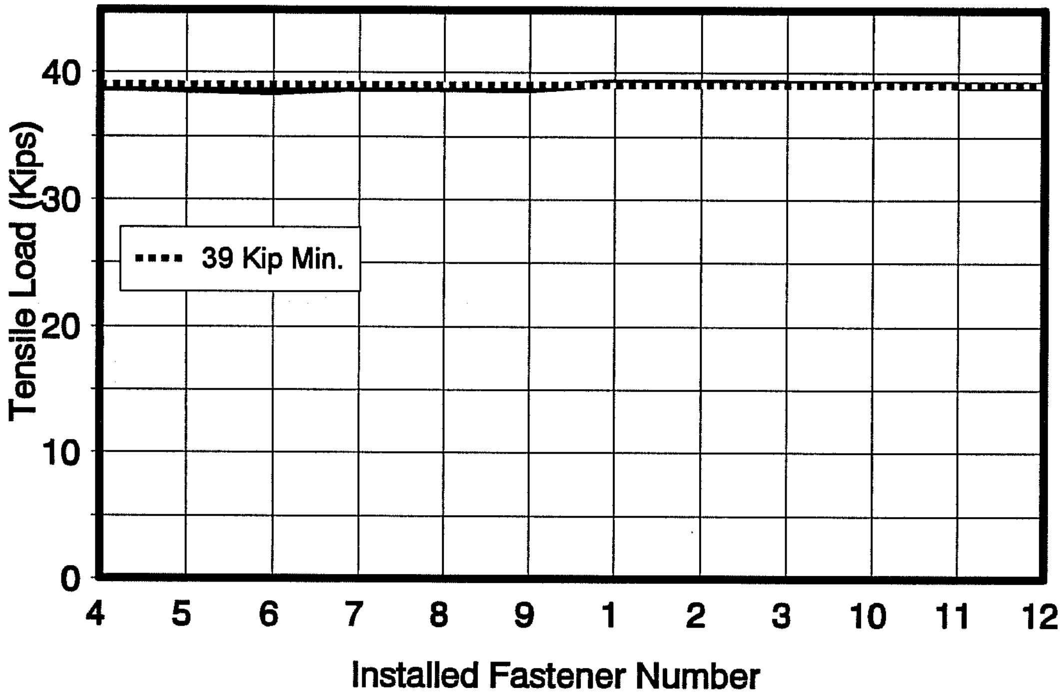


Figure 4.7: Tensile Load History for Fastener #4 - Test CFCWNS-2

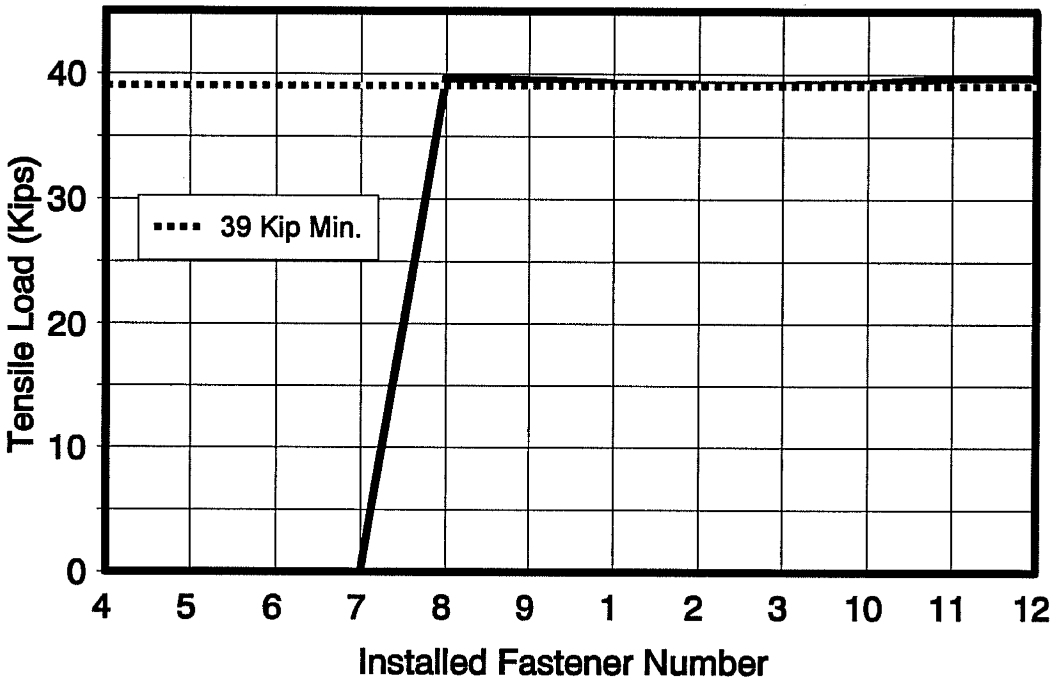


Figure 4.8: Tensile Load History for Fastener #8 - Test CFCWNS-2

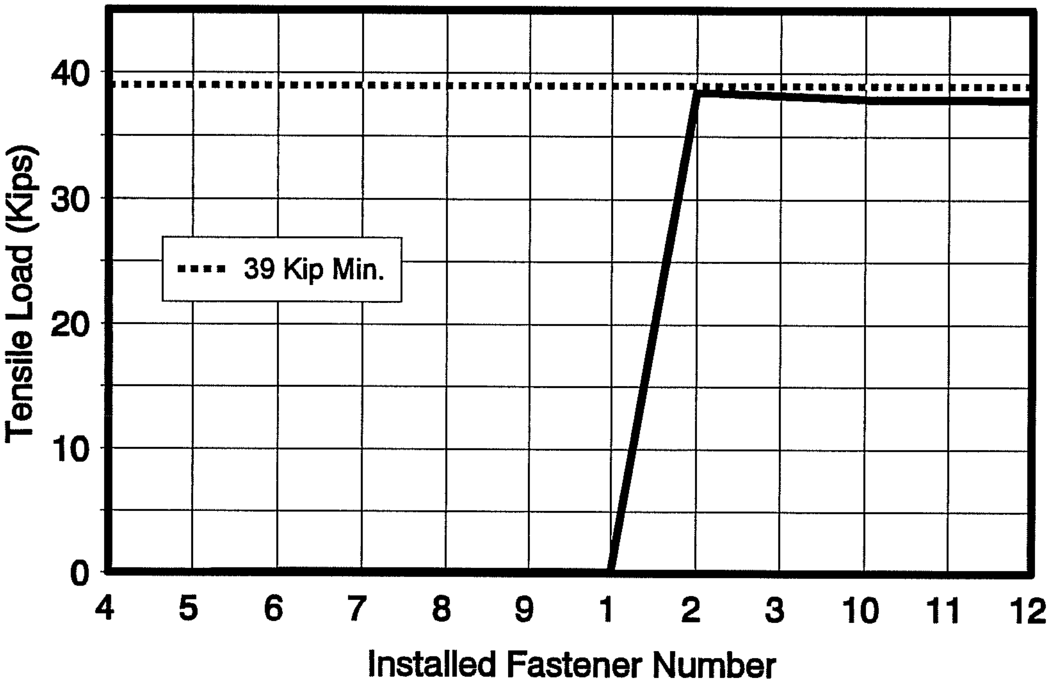


Figure 4.9: Tensile Load History for Fastener #2 - Test CFCWNS-2

Fastener Number

Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	46.1	0	0	0.0	-0.1	0	0	-0	0.2	-0	0	0
5.0	45.3	37.1	-0	0.0	-0	-0	0.0	0.0	0.0	-0	0.0	0
6.0	44.9	36.8	39.3	-0	-0.1	-0	0.0	-0	0	-0.1	0	0.1
7.0	45.3	37.1	38.9	43.3	-0	0.0	0	-0	0	-0.1	-0	-0
8.0	45.4	37.1	38.9	42.0	42.6	-0	0.0	0.0	0	-0.1	0.0	0.0
9.0	45.3	37.2	38.9	41.8	42.1	40.0	0	-0	0	-0.1	0.0	-0
1.0	46.0	38.1	39.0	41.7	42.0	39.4	42.9	-0	0	-0.1	-0	-0
2.0	46.1	38.3	39.2	41.7	41.9	39.3	42.0	41.3	0	-0.1	0.0	-0
3.0	46.0	38.5	39.3	41.6	41.8	39.2	41.9	41.0	38.1	-0.1	-0	-0
10.0	46.0	38.4	39.3	41.3	42.1	39.1	41.9	41.0	37.6	45.2	0.0	-0
11.0	46.0	38.4	39.3	41.4	42.0	39.3	41.9	40.9	37.5	44.4	38.6	0.0
12.0	46.0	38.4	39.3	41.4	42.1	39.1	41.9	40.9	37.4	44.3	38.0	41.8

Tension in Kips

Average Fastener Tension = 40.9 Kips

4-1/4" Conventional Fasteners
3" Grip
Flat Plates
Cal. Wrench Installation
(w/o Snugging)

1	4	7	10
2	5	8	11
3	6	9	12

Fastener Numbers

Figure 4.10: Fastener Tensions for Test CFCWNS-3

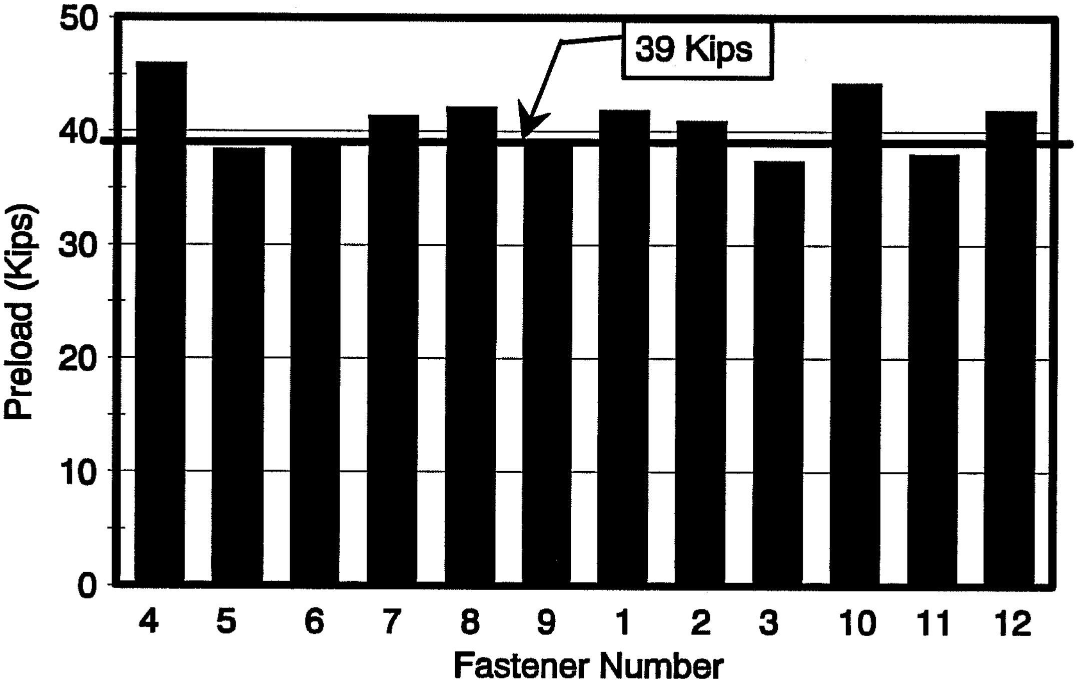


Figure 4.11: Final Installed Tensions for Test CFCWNS-3

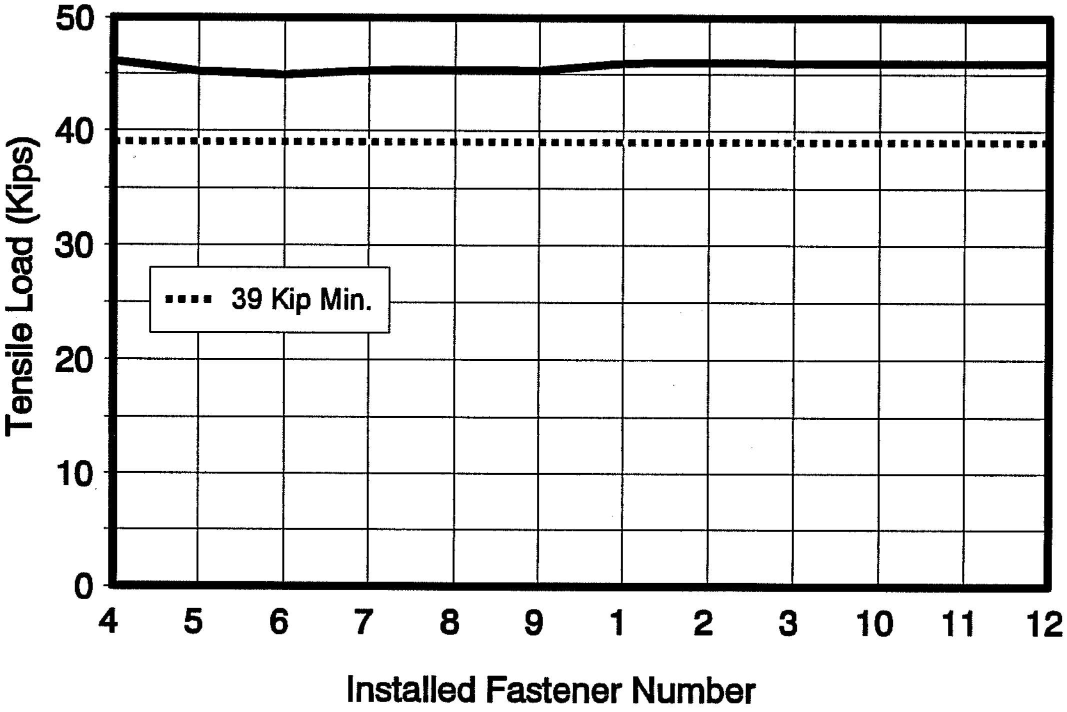


Figure 4.12: Tensile Load History for Fastener #4 - Test CFCWNS-3

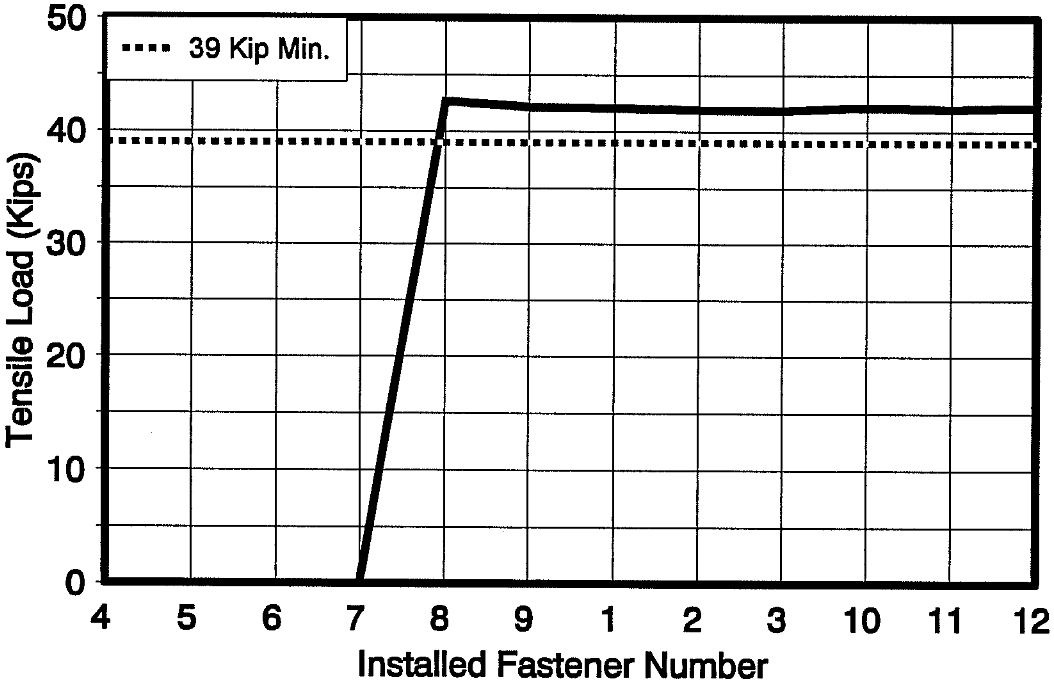


Figure 4.13: Tensile Load History for Fastener #8 - Test CFCWNS-3

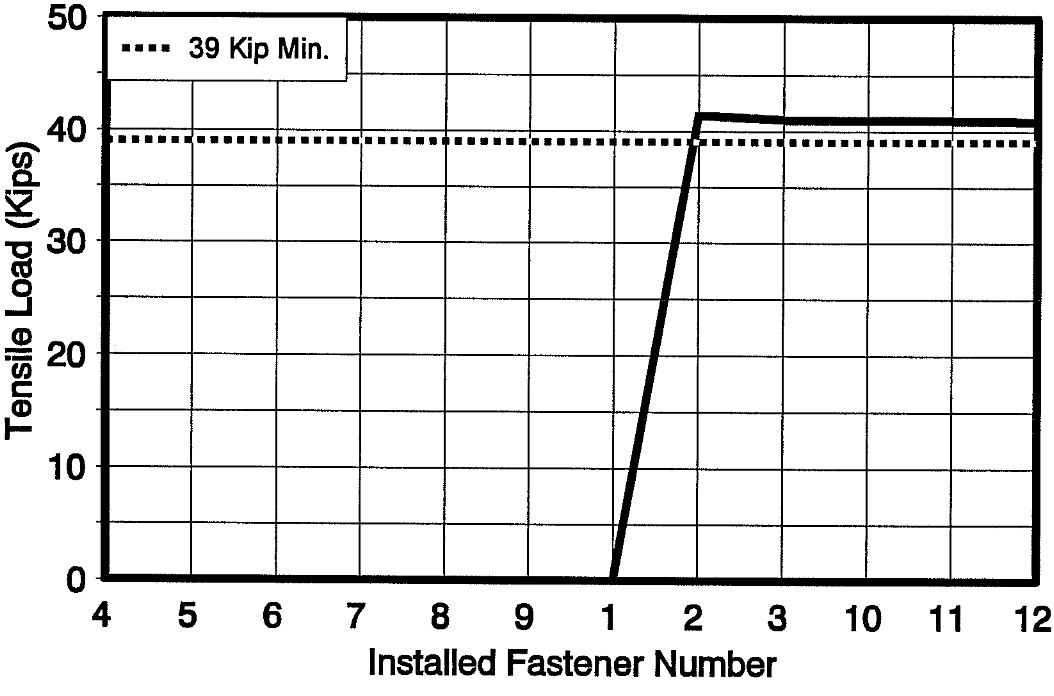


Figure 4.14: Tensile Load History for Fastener #2 - Test CFCWNS-3

Fastener Number

Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	43.8	-0	0	0.0	0	-0	0.0	0.0	-0	0	0.0	-0
5.0	42.5	45.0	-0	-0	-0	-0	-0	-0	-0.1	0.0	-0	-0
6.0	42.5	43.5	44.7	-0	-0	-0	-0	-0	-0.1	0	-0	-0
7.0	41.8	43.4	44.1	42.1	-0	-0.1	-0	-0	-0.1	0	-0	-0
8.0	41.9	43.2	44.1	41.1	46.8	-0.1	-0	-0	-0.1	0	-0	-0
9.0	41.9	43.2	43.3	40.9	45.6	47.1	-0.1	-0.1	-0.2	0	-0.1	-0.1
1.0	42.0	43.4	43.4	40.8	45.5	46.2	41.3	-0.1	-0.2	0.1	-0	-0.1
2.0	42.2	43.4	43.6	40.8	45.4	46.1	40.2	43.2	-0.2	0.1	-0	-0.1
3.0	42.2	43.5	43.5	40.7	45.4	46.1	40.1	41.9	39.4	0.1	-0	-0.1
10.0	42.2	43.5	43.5	40.1	45.6	46.2	39.9	41.7	38.7	43.7	-0	-0.1
11.0	42.2	43.5	43.5	40.1	45.3	46.2	39.9	41.6	38.5	42.5	42.1	-0.1
12.0	42.2	43.5	43.5	40.1	45.3	45.7	39.8	41.6	38.4	42.3	40.4	40.6

Tension in Kips

Average Fastener Tension = 42.0 Kips

5-1/4" Conventional Fasteners
4" Grip
Flat Plates
Cal. Wrench Installation
(w/o Snugging)

1	4	7	10
2	5	8	11
3	6	9	12

Fastener Numbers

Figure 4.15: Fastener Tensions for Test CFCWNS-4

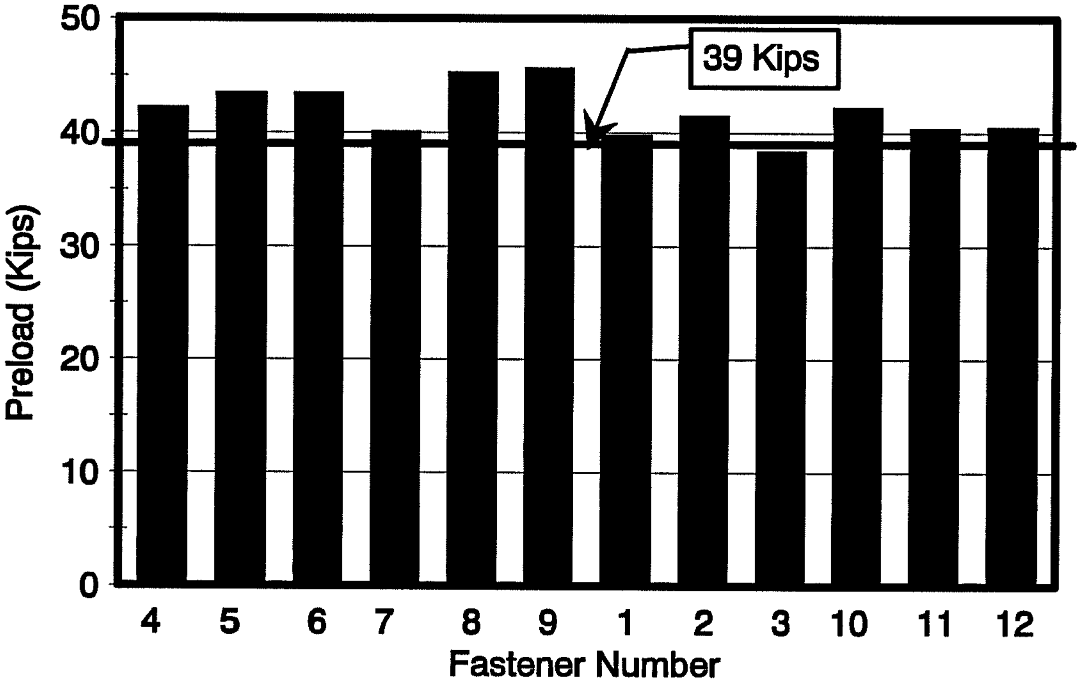


Figure 4.16: Final Installed Tensions for Test CFCWNS-4

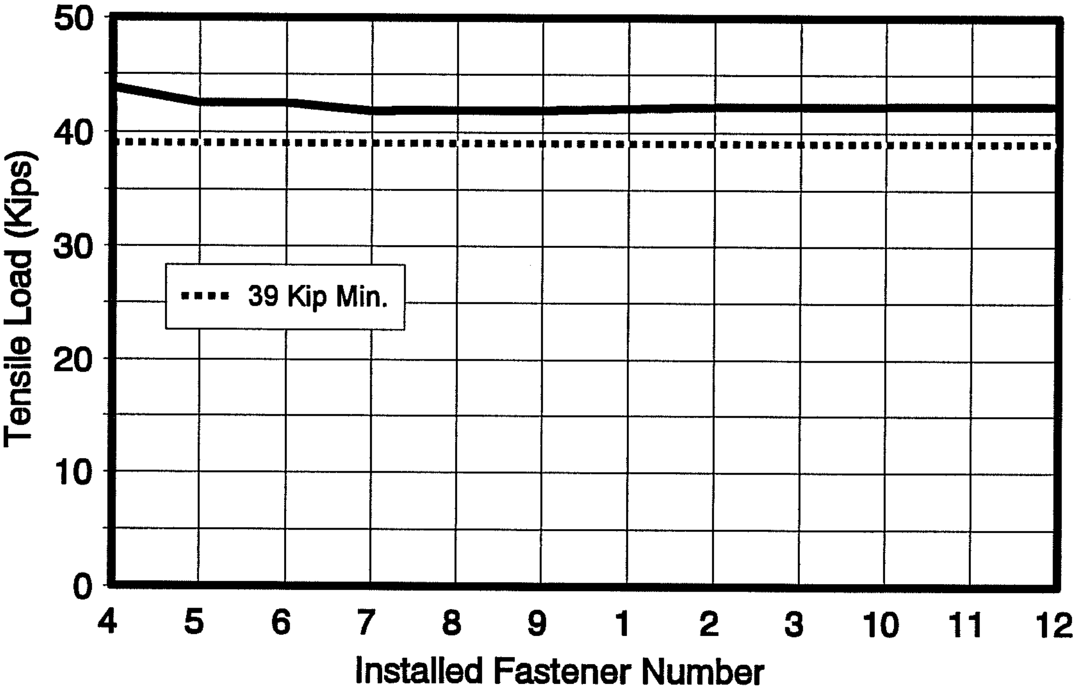


Figure 4.17: Tensile Load History for Fastener #4 - Test CFCWNS-4

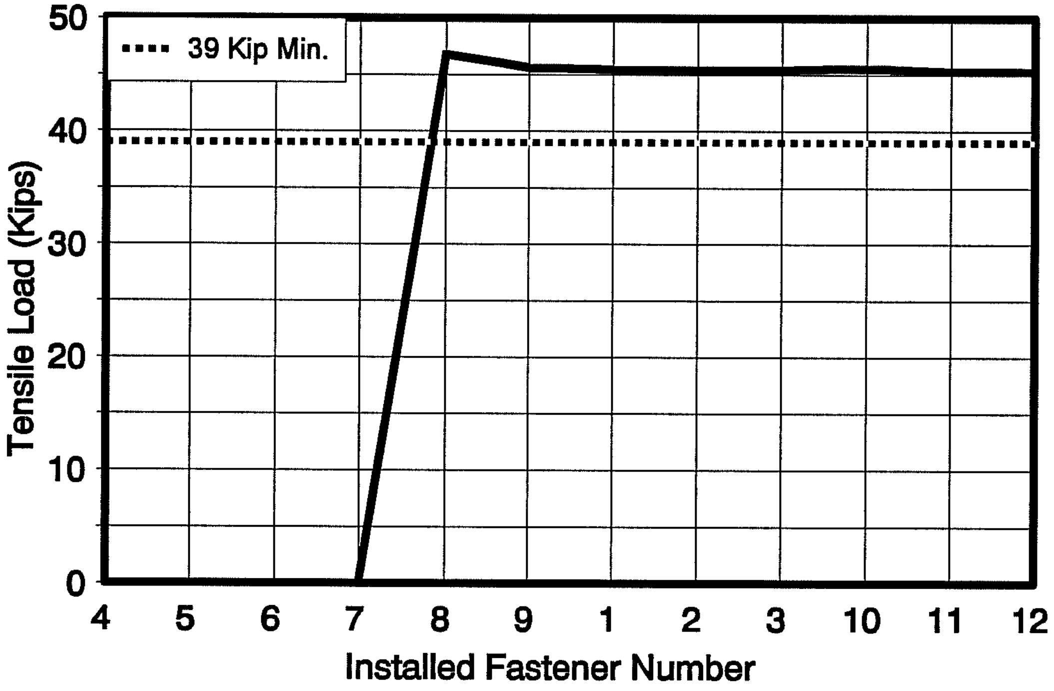


Figure 4.18: Tensile Load History for Fastener #8 - Test CFCWNS-4

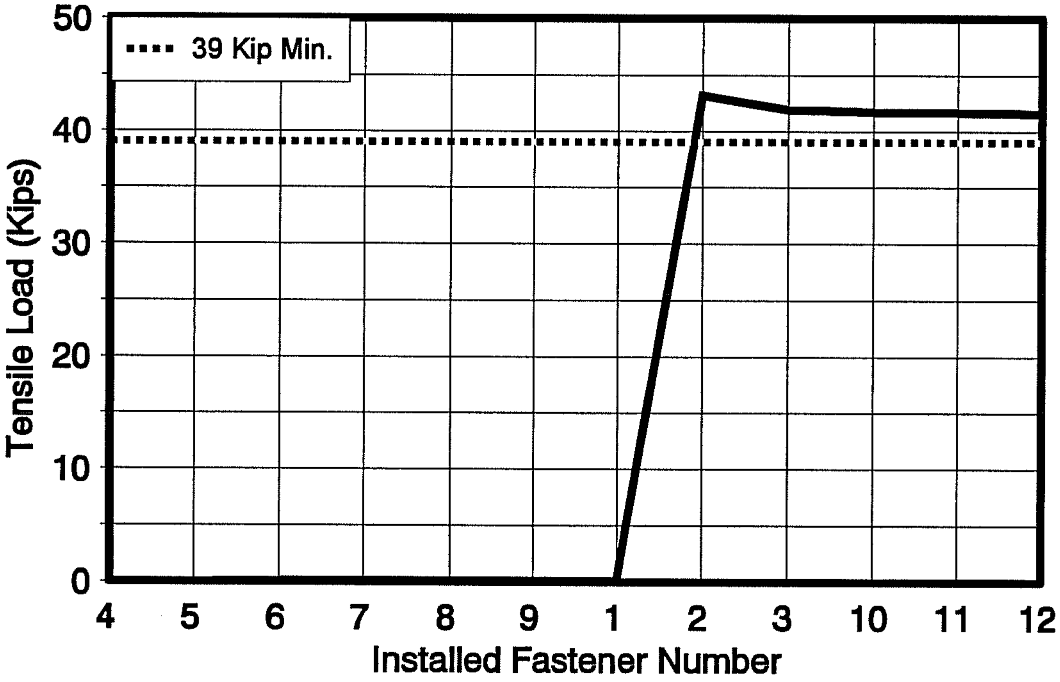


Figure 4.19: Tensile Load History for Fastener #2 - Test CFCWNS-4

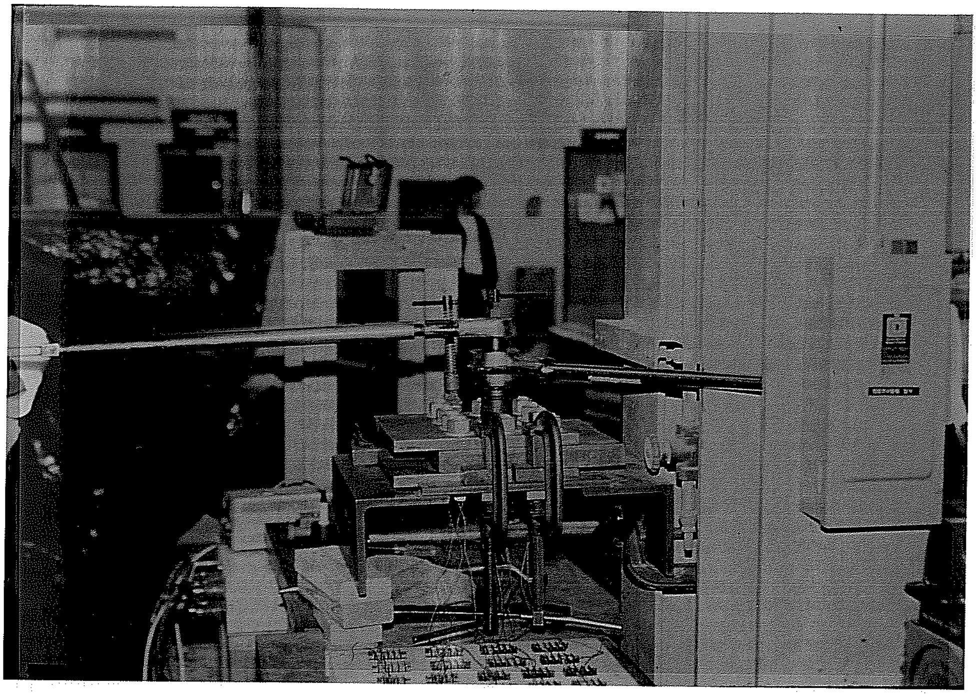


Figure 4.20: Torque wrench and 4X torque multiplier

jarring due to wrench impact on the adhesive of the strain gauged fastener. Damage to the gauges with consequent inaccurate readings was seen as a possible result of impact wrench use, thus, the torque wrench and multiplier were utilized to alleviate this concern. In addition to providing a more static torque load to the fasteners, the torque wrench allowed for a more accurate determination of the degree of nut rotation past snug tight.

The fasteners (nuts, bolts, and washers) used in the turn-of-nut tests were the identical fasteners used in the calibrated wrench tests of Section 4.2.1. Because the torque-controlled loads of these tests were well below the yield loads of the fasteners (even in the threaded portions), it was decided that the bolts could be reused. Prior to turn-of-nut testing, all bolts, nuts, and washers were cleaned of any galvanization that may have galled off during the previous installation. All fastener components were discarded upon the completion of the turn-of-nut tests.

All tests in this section fall under the CFTON series designation.

4.2.2.1 TEST RESULTS

During the turn-of-nut tests, the possibility of yielding in the unthreaded portion of the bolt shanks had to be addressed. As noted in Section 3.4.6, the presence of residual strains (upon fastener unloading) in the gauges would indicate such yielding. For the turn-of-nut tests, (both on flat and deformed plates) readings of BTM gauge strain were monitored during bolt snugging, tightening, and after loosening of all bolts. In the flat plate tests for each grip length, some yielding occurred in the unthreaded fastener shanks. Because of this yielding and the requirement of residual strain measurement to determine elastic strain, the only values of fastener load that could be accurately determined (besides snug loads) were the final installed values. Thus, the results of each test will show only the loads recorded in each bolt during the snugging process and the final load in each fastener after tightening. No intermediate tightening loads are given. These final installed fastener tensions are denoted by the word "Final" or simply by the letter "F" in the figures describing the results of the flat plate, turn-of-nut tests and are calculated as described in Section 3.4.6.

In addition to the yielding in the unthreaded shank, plastic deformation in the bolt threads was also evident. Upon removing the fasteners from the splice connection after testing, the nuts could not be installed onto the fasteners over the entire length of the threads (i.e. they could not be turned on the threads to the thread run-out). Thus, some permanent elongation was induced in the threads of the fasteners by the high tensile loads developed during turn-of-nut installation.

Table 4.2 is a summary of the important fastener tensile load results that were observed during these tests. The table lists the average values of final fastener tension, initial snug fastener tension, and fastener tension loss during the snugging pass. The final tensions are those measured in the bolts subsequent to the tightening of the last bolt in the connection by measured nut rotation past snug tight. Initial snug fastener tension refers to the tension developed in that fastener immediately after snugging of that fastener during the snugging pass. Snug tension loss is the difference between the initial snug load of a fastener and the load in the same fastener upon completion of the snugging pass for all connection fasteners. Standard deviations for all quantities are also listed.

Test CFTON-2:

Figures 4.21 to 4.25 and Table 4.2 present the results of this test. The final average installed fastener tension was 54.5 kips per Figure 4.21. Loss of tension in snugged fasteners was almost negligible during the snugging process; the average loss of load was 0.4 kips as shown in Table 4.2. Figures 4.23, 4.24, and 4.25 show this trend in the graphical load histories of bolts 4, 8, and 2. A wide variation in the initial snug loads in the bolts is seen in the form of a 2.3 kip standard deviation from the mean value of 26.1 kips (Table 4.2). The maximum variation in initial fastener snug load was 7.6 kips as shown in Figure 4.21.

Test #	**Average Final Fastener Tension**	**Standard Deviation**	**Average Initial Snug Tension**	**Standard Deviation**	**Average Snug Tension Loss**	**Standard Deviation**
CFTON-2	54.5	2.6	26.1	2.3	0.4	0.4
CFTON-3	51.7	2.2	33.6	3.1	0.1	0.7
CFTON-4	55.0	2.7	30.2	2.1	0.8	0.3

Note: All values in Kips

Table 4.2: Summary of fastener load results for CFTON series tests

Test CFTON-3:

The results of this 3" grip test are detailed in Figures 4.26 through 4.30 and Table 4.2. The average installed final fastener tension was 51.7 kips (Table 4.2), well above the 39 kip minimum value. Similar to test CFTON-2, the snug loads in the bolts stayed relatively constant during the snugging process. The average snug tension loss, as indicated in Table 4.2, was a minuscule 0.1 kips. Figures 4.28, 4.29, and 4.30 show the relatively constant tensile loads for fasteners 4, 8, and 2 during snugging, as well as the high final tensions in the bolts after final tightening (column "F" on the horizontal axis of the plots). The initial snug loads induced in the individual fasteners varied widely, with a standard deviation of 3.1 kips from the 33.6 kip mean value (see Table 4.2).

Test CFTON-4:

Figures 4.31 to 4.35 and Table 4.2 present the results of this 4" grip connection test. Similar to the previous two flat plate, turn-of-nut tests, the average final fastener tension of 55 kips well exceeded the required 39 kips. Loss of load in the individual bolts due to snugging of subsequent fasteners was higher than in the previous tests (0.8 kips - Table 4.2) but was not large in relation to the magnitudes of the snug loads themselves. Figures 4.33, 4.34, and 4.35 show the relatively constant snug load values in fasteners 4, 8, and 2. As in tests CFTON-2 and CFTON-3, the values of snug tension initially induced in the connection fasteners were inconsistent, with a

Fastener Number

Snugging Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	26.0	0.5	0.3	0.2	0.1	0.4	0.3	0.8	0.4	0.3	0.5	0.1
5.0	25.3	30.6	0.2	0.1	-0	0.2	0.1	0.2	0.1	0	0.3	-0.1
6.0	25.2	30.3	23.7	0.2	-0.1	0.3	0.3	0.3	0.3	0.3	0.7	-0
7.0	25.1	29.9	23.0	26.3	-0.1	-0.1	-0.1	0.1	0	-0.1	-0.1	-0.1
8.0	25.0	29.9	22.8	26.2	24.8	0.1	0.2	0.1	0.4	0.2	0.2	-0.1
9.0	24.9	29.8	22.6	25.9	24.8	26.6	-0.1	-0	-0	-0.2	-0.2	-0.2
1.0	25.6	30.1	22.7	26.0	24.7	26.2	27.9	0.1	0.2	0	0.1	-0
2.0	25.8	30.5	22.7	25.9	24.7	26.1	27.5	29.4	0.1	-0.1	0	-0.1
3.0	26.0	30.7	23.3	25.5	24.8	25.7	26.9	29.3	25.8	-0.4	-0.3	-0.1
10.0	25.7	30.6	23.2	26.6	24.8	26.3	27.4	29.2	26.1	24.6	0.4	0.1
11.0	25.6	30.6	23.2	26.3	25.2	26.0	26.9	29.0	25.6	24.1	25.4	-0.1
12.0	25.6	30.5	23.1	26.0	25.1	26.1	26.7	29.1	25.4	23.7	25.0	21.8
Final	49.9	55.9	57.0	49.9	59.3	54.3	53.1	54.4	55.8	54.7	56.0	54.0

Tension in Kips

Average Fastener Tension = 54.5 Kips

3-1/4" Conventional Fasteners
2" Grip
Flat Plates
Turn-of-Nut Installation

1	4	7	10
2	5	8	11
3	6	9	12

Bolt Numbers

Figure 4.21: Fastener Tensions for Test CFTON-2

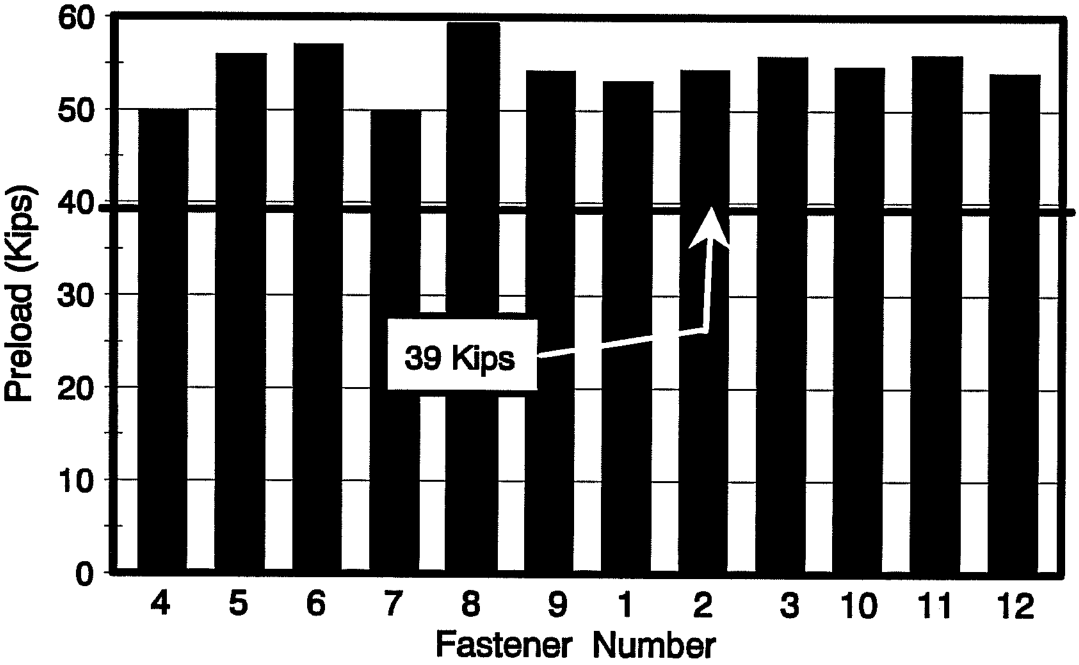


Figure 4.22: Final Installed Tensions for Test CFTON-2

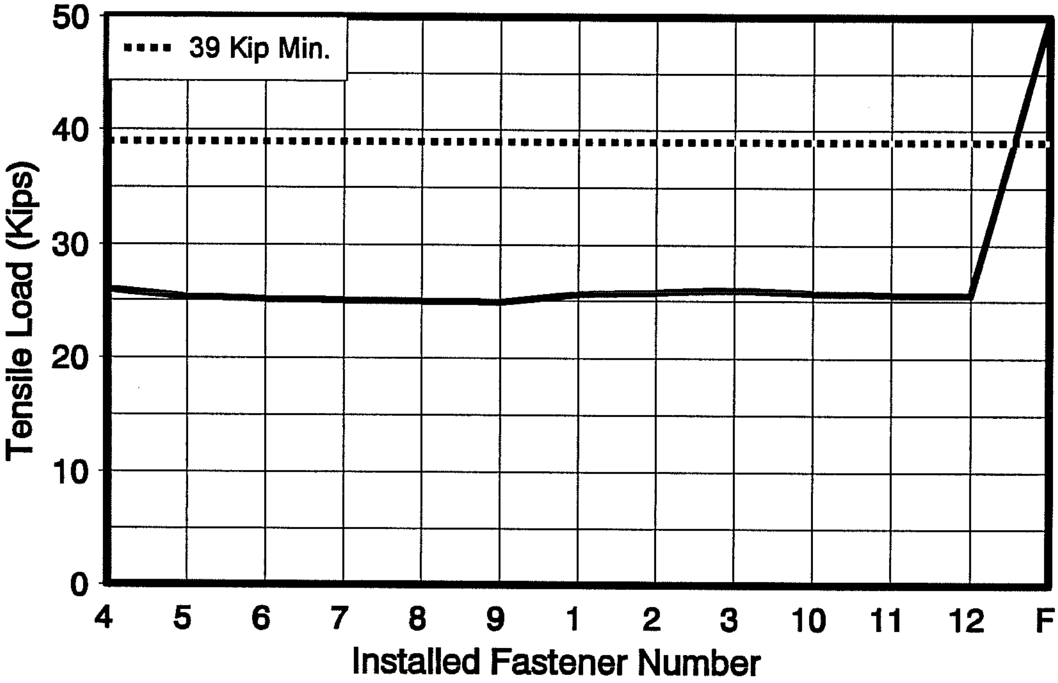


Figure 4.23: Tensile Load History for Fastener #4 - Test CFTON-2

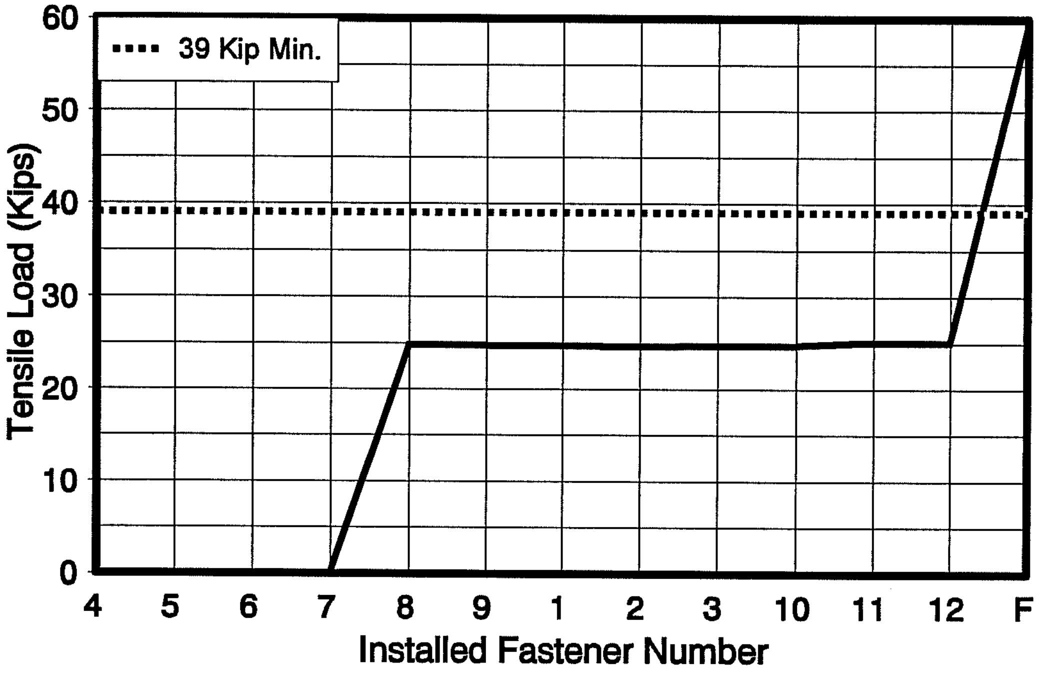


Figure 4.24: Tensile Load History for Fastener #8 - Test CFTON-2

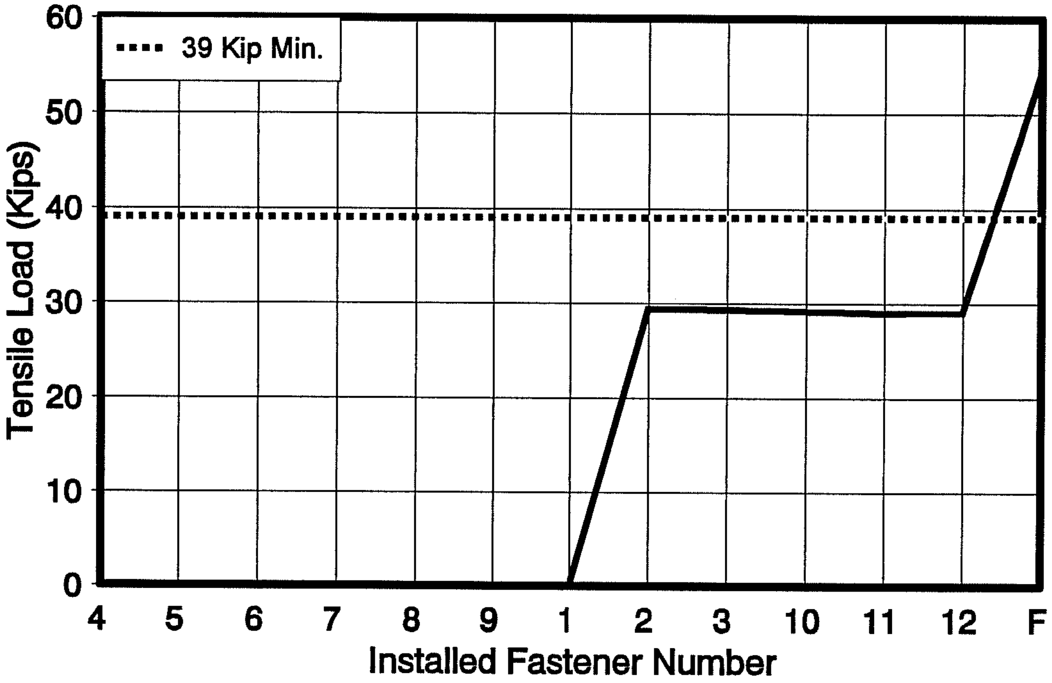


Figure 4.25: Tensile Load History for Fastener #2 - Test CFTON-2

Fastener Number

Snugging Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	29.5	-0	0	0	0.0	0.1	0	-0.1	0.1	0.1	0.1	-0.1
5.0	29.8	32.0	0.6	0.1	0.6	0.2	0	0.2	0	0.1	0.2	0.1
6.0	29.5	31.7	29.2	0.1	0.6	0.2	-0	0.5	0	0.1	0.2	0.1
7.0	29.6	31.5	28.6	32.4	0	0.3	0	0.2	0	0.2	0.2	0.1
8.0	30.0	31.9	29.1	32.1	36.0	0.3	-0	0.2	0.1	0.1	0.2	-0
9.0	29.6	31.9	29.0	31.9	35.4	35.3	-0	-0.1	-0	0.1	0	-0
1.0	30.5	32.5	29.2	31.8	35.3	35.0	32.8	-0	-0	0.1	0.1	-0.1
2.0	31.0	33.2	29.7	31.9	35.5	34.9	32.8	33.9	0	0.1	0.1	-0.1
3.0	31.1	33.6	29.8	31.8	35.7	34.9	32.7	34.2	41.8	0.1	0.2	0.2
10.0	30.6	33.1	29.4	31.7	35.1	34.7	32.7	33.6	41.3	32.6	0.1	0
11.0	30.7	33.2	29.4	31.8	35.4	34.8	32.6	33.6	41.2	32.2	33.7	0
12.0	30.7	33.2	29.5	31.8	35.5	34.7	32.6	33.6	41.1	32.1	33.3	33.4
Final	52.1	53.7	49.9	50.6	53.1	52.0	53.6	56.1	48.2	51.7	50.6	48.3

Tension in Kips

Average Fastener Tension = 51.7 Kips

4-1/4" Conventional Fasteners
3" Grip
Flat Plates
Turn-of-Nut Installation

1	4	7	10
2	5	8	11
3	6	9	12

Fastener Numbers

Figure 4.26: Fastener Tensions for Test CFTON-3

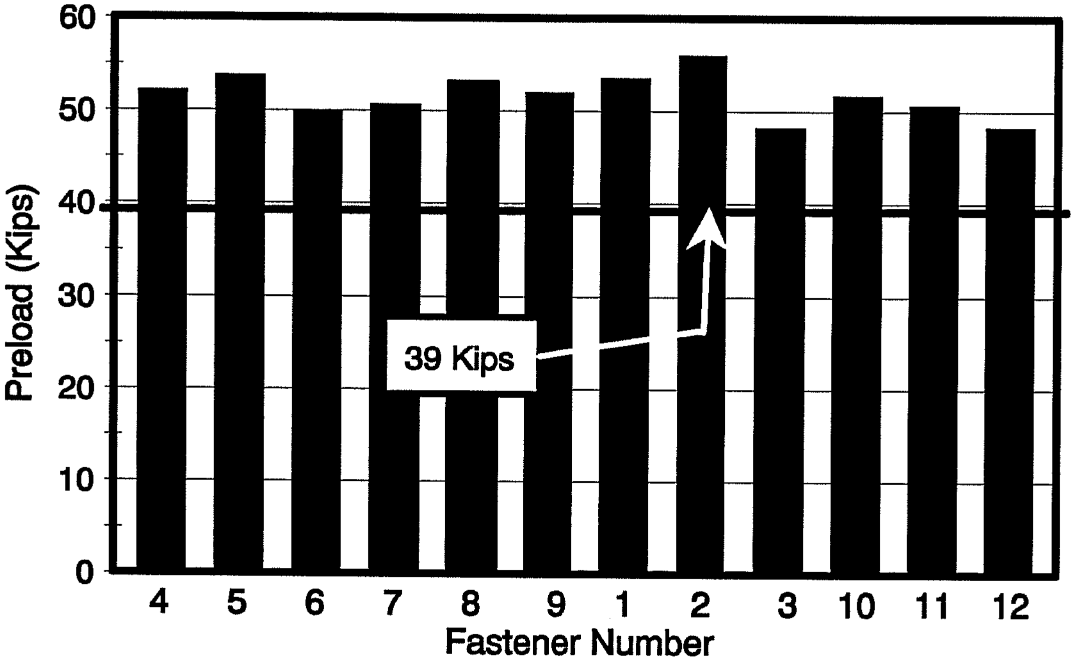


Figure 4.27: Final Installed Tensions for Test CFTON-3

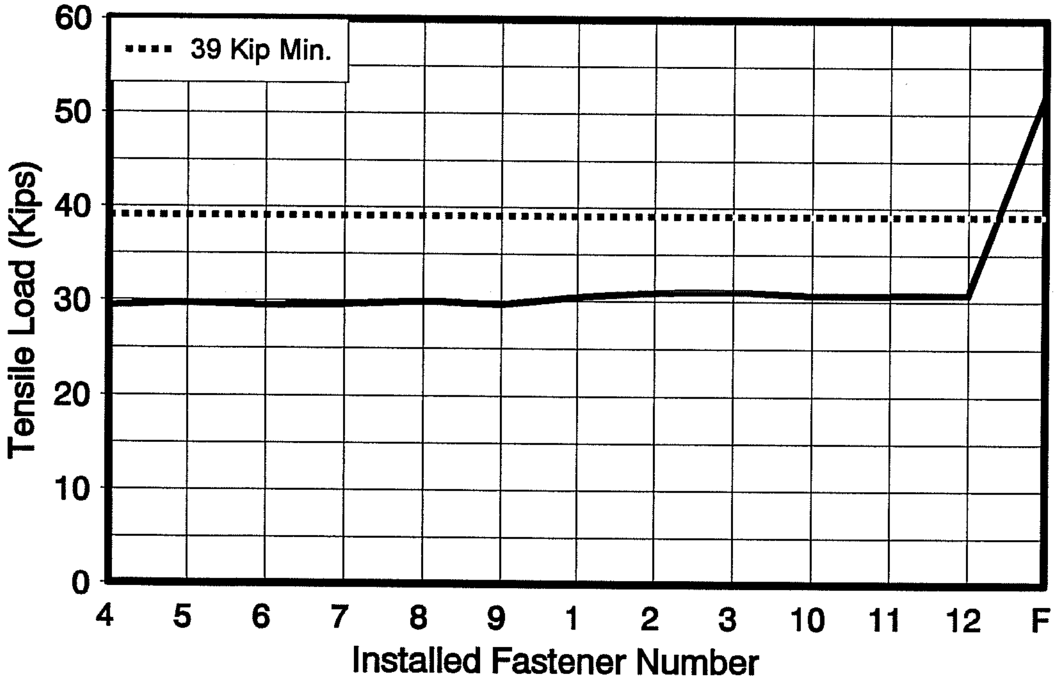


Figure 4.28: Tensile Load History for Fastener #4 - Test CFTON-3

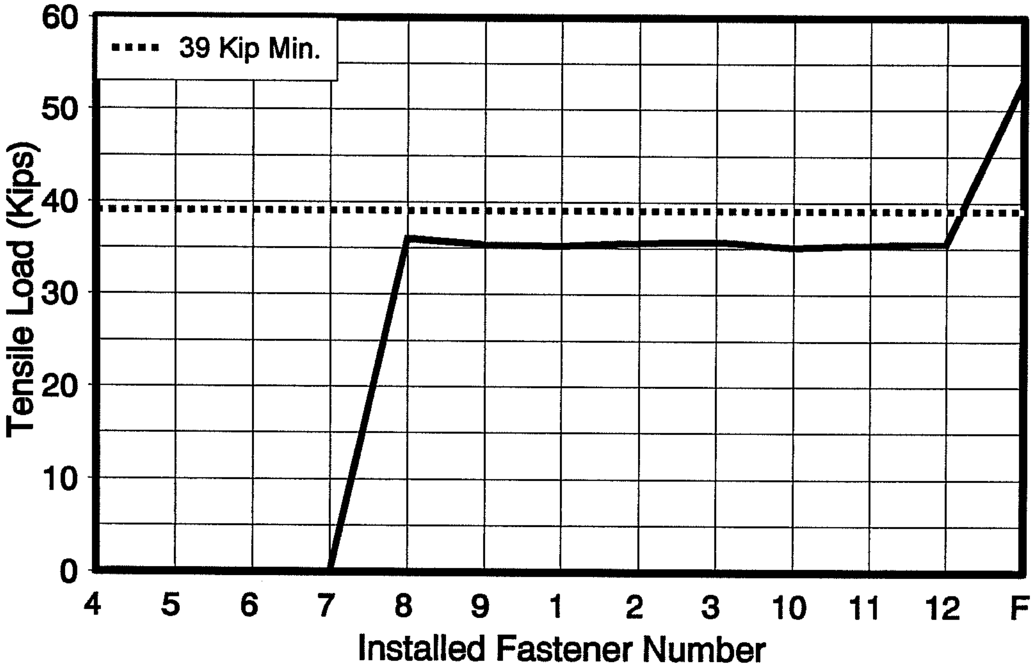


Figure 4.29: Tensile Load History for Fastener #8 - Test CFTON-3

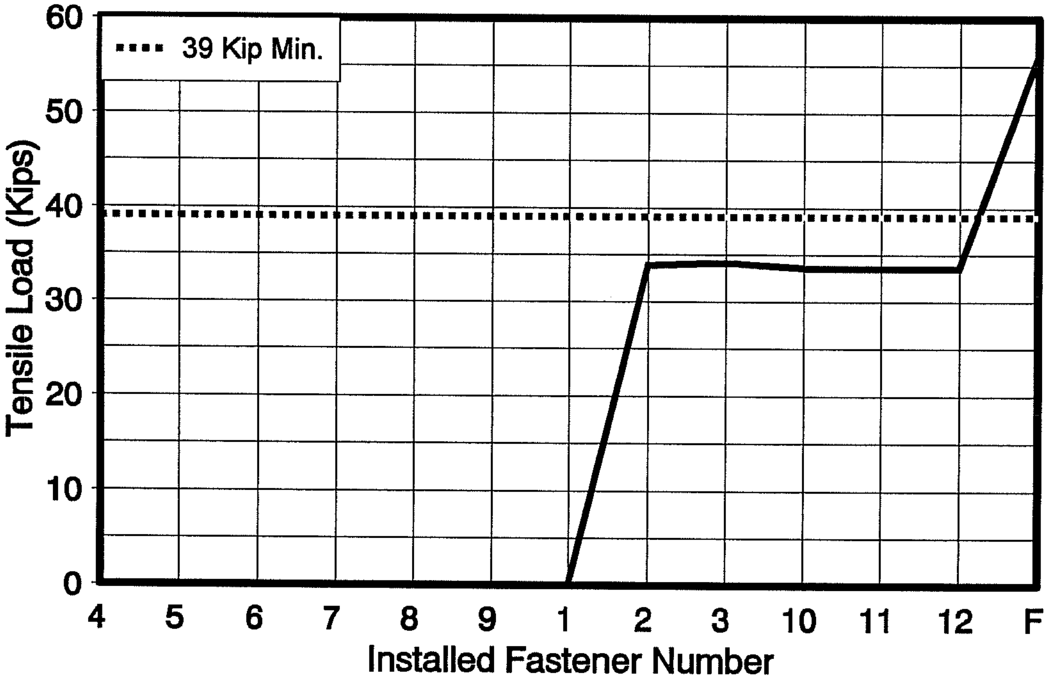


Figure 4.30: Tensile Load History for Fastener #2 - Test CFTON-3

Fastener Number

Snugging Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	32.6	-0.4	-0.5	0	-0.1	-0.1	0	-0.3	-0.1	-0.3	-0.2	-0.2
5.0	31.0	33.1	-0.3	-0.1	0	0.1	0	-0.2	-0.1	-0	0	-0
6.0	30.6	31.1	30.7	-0	-0.2	-0.1	-0.1	-0.5	-0.1	-0.2	-0.2	-0.2
7.0	29.9	31.3	30.6	32.3	-0.1	-0	0	-0.5	0.0	-0.1	-0.1	-0.2
8.0	30.4	31.4	31.1	31.7	27.4	-0.1	0	-0	-0	-0.1	-0	-0
9.0	30.6	31.6	29.9	31.5	26.6	27.1	-0	0.1	-0	-0.1	-0.1	-0
1.0	30.4	31.6	29.7	31.4	26.1	26.6	32.1	-0.4	-0.1	-0.2	-0.1	-0
2.0	30.7	31.7	30.0	31.3	26.0	26.4	31.5	30.4	-0.1	-0.2	-0.1	0
3.0	30.5	31.7	29.7	31.3	25.9	26.4	31.5	29.6	29.3	-0.2	-0.1	0
10.0	31.0	32.3	30.2	31.2	26.4	26.6	31.5	30.0	28.9	32.0	-0	0
11.0	31.0	32.2	30.1	31.3	26.1	26.6	31.5	29.8	28.8	31.6	27.3	0
12.0	31.0	32.2	30.2	31.3	26.2	26.4	31.4	29.7	28.7	31.6	26.4	28.5
Final	58.5	53.1	52.0	56.5	56.5	56.9	48.7	54.8	56.3	54.9	58.6	53.7

Tension in Kips

Average Fastener Tension = 55.0 Kips

5-1/4" Conventional Fasteners
4" Grip
Flat Plates
Turn-of-Nut Installation

1	4	7	10
2	5	8	11
3	6	9	12

Fastener Numbers

Figure 4.31: Fastener Tensions for Test CFTON-4

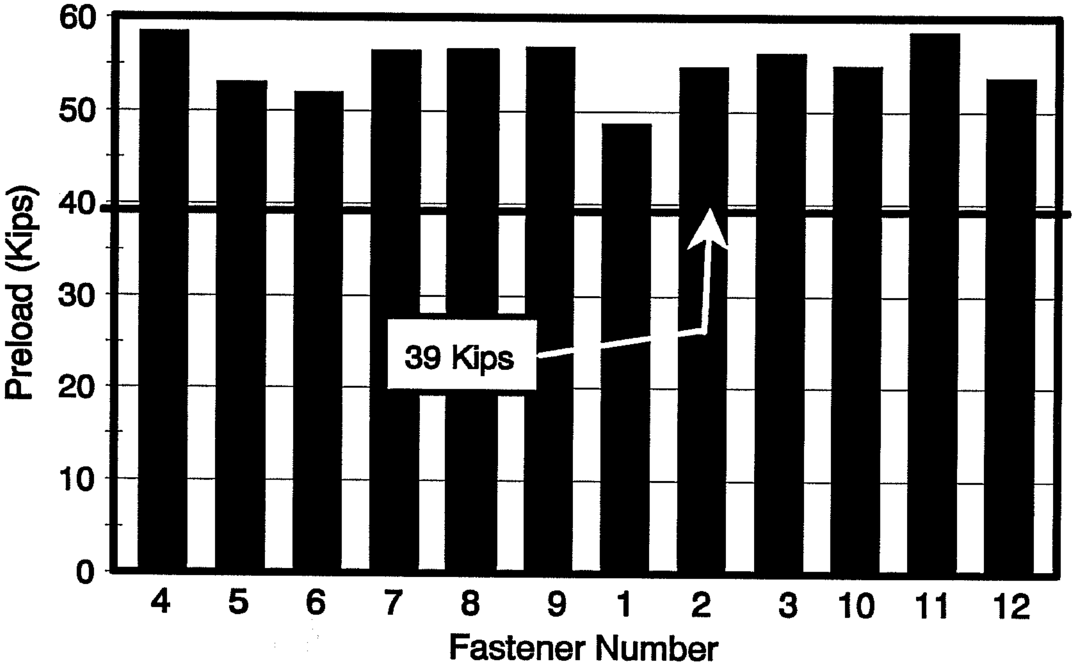


Figure 4.32: Final Installed Tensions for Test CFTON-4

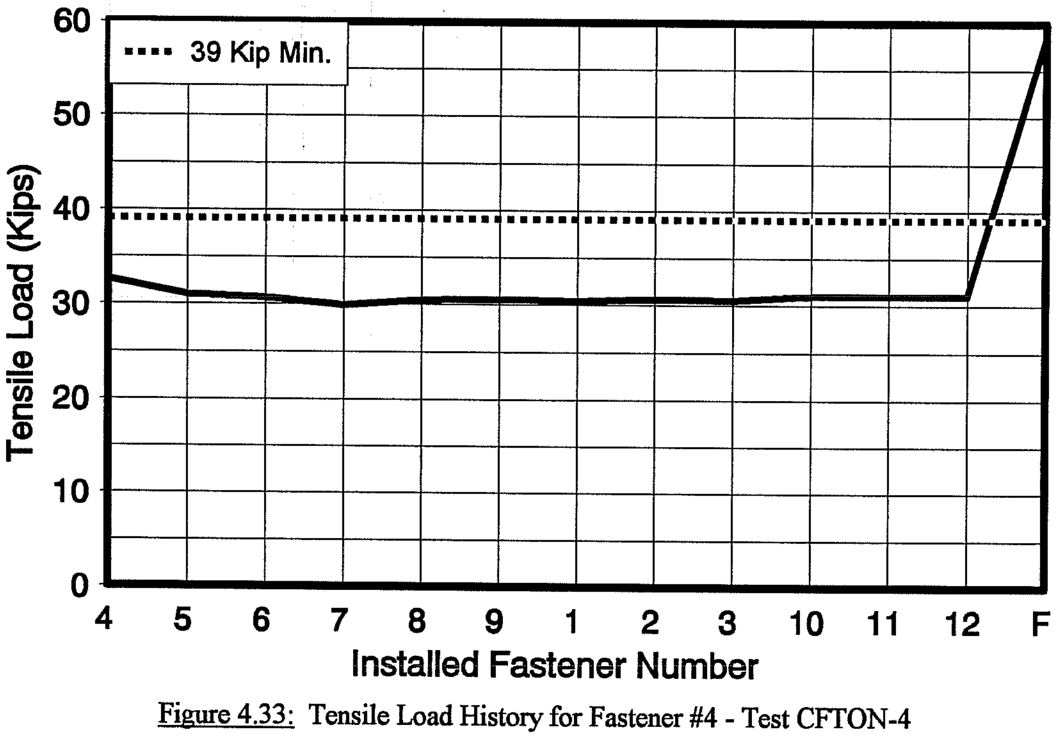


Figure 4.33: Tensile Load History for Fastener #4 - Test CFTON-4

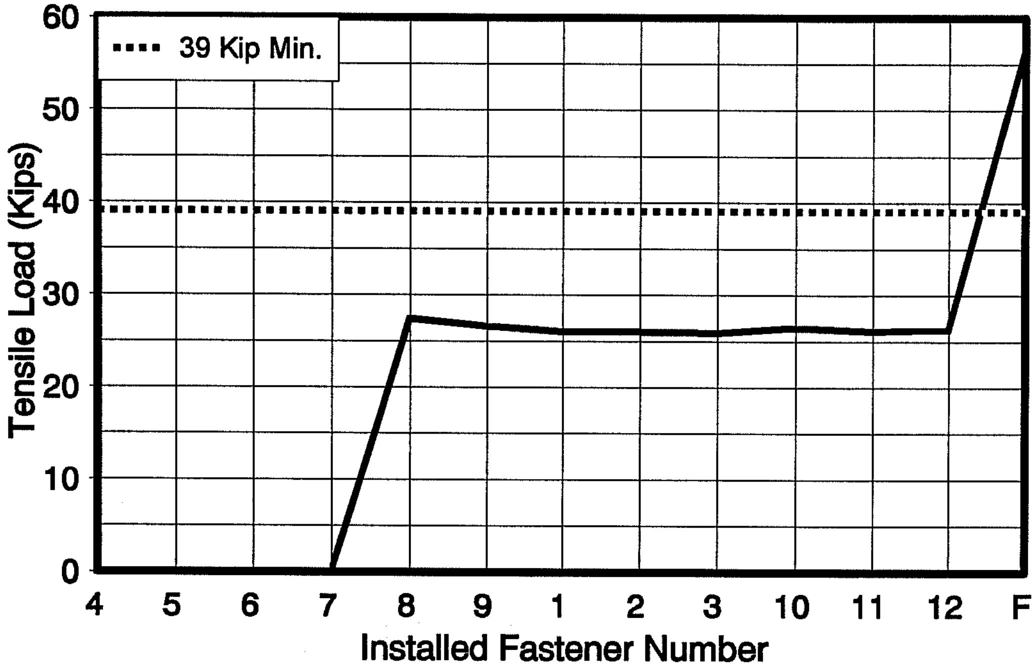


Figure 4.34: Tensile Load History for Fastener #8 - Test CFTON-4

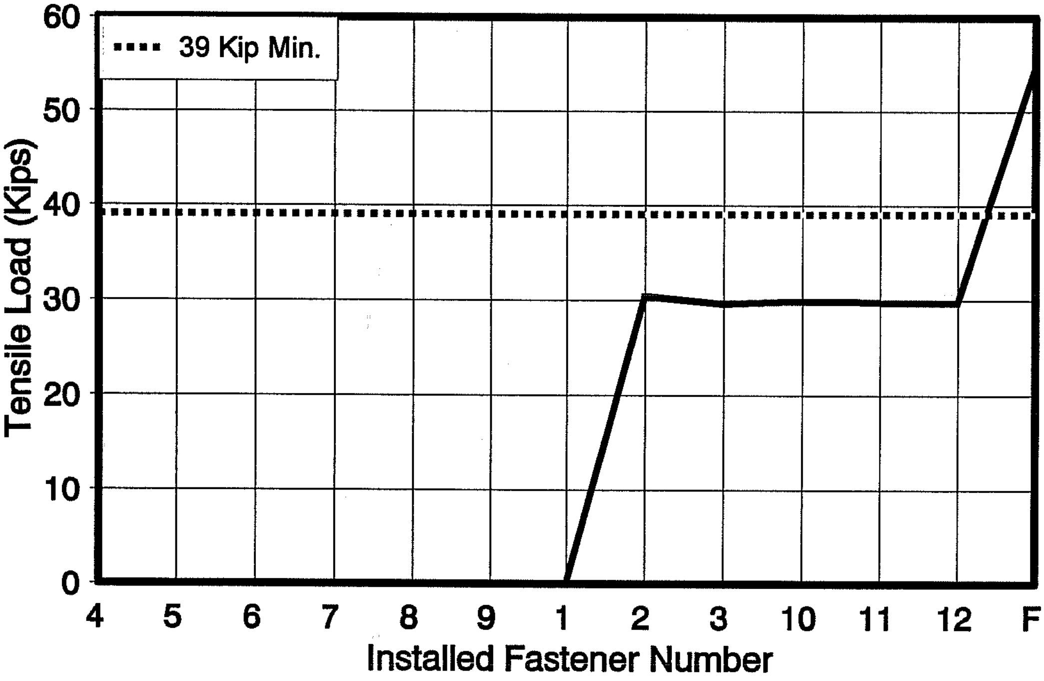


Figure 4.35: Tensile Load History for Fastener #2 - Test CFTON-4

2.1 kip standard deviation from the mean value of 30.2 kips. Figure 4.31 shows that the maximum variation was 6.0 kips between fastener 5 and fastener 9.

4.3 DEFORMED PLATE TESTS

For these tests, the middle plate of each connection was deformed in single curvature bending to a deflection of 3mm, as described in Section 4.1. Figure 4.1 illustrates the deformed plate condition.

Plate out-of-flatness was determined by first measuring the thickness of the plate in question (at the mid-point of one side) with a set of precision calipers. Next, the exact thickness of a piece of 1/2"x14"x3/8" flat bar was measured at the mid-point of the length. To determine the deformation of the plate, the bar stock was laid along the plate edge that had been previously measured for thickness so that the points of known thickness on both the flat bar and the plate (the mid-points) were aligned. The distance from the top of the flat bar to the bottom of the plate was then measured. By subtracting the known thicknesses of the plate and flat bar from this amount, the deflection of the plate was determined. After each test, the plates in the connection were checked as just described for changes in their condition due to the clamping effects of the installed fasteners. The outer plates were verified for flatness while the inner plate was measured to insure that it retained its prescribed 3mm deformation. The plates were rebent as necessary to ensure the correct plate conditions.

The deformed plate tests were conducted on all three grip lengths and fastener installation was conducted by three methods:

1.) Calibrated wrench without snugging
2.) Calibrated wrench with snugging
3.) Turn-of-nut

4.3.1 CALIBRATED WRENCH (w/o SNUG) INSTALLATION METHOD

These tests were conducted with a single installation pass using a torque wrench set to develop 41 kips of tension in the fasteners (see Section 4.2.1). As described in that section, the torque required to develop 41 kips of tension in the fasteners was verified in the Skidmore-Wilhelm bolt tension indicator prior to the commencement of testing. This installation technique used in these tests allows a comparison of these results to those obtained by single pass installation of the Huck fasteners in similarly deformed plates. For the 3" and 4" grip tests, an additional "touch-up" pass was performed after tightening to determine the ability of a second torquing to induce in the connection fasteners an adequate level of tensile load. This touch-up pass was completed by applying another tightening to the connection fasteners (in the same installation order) with the torque wrench set to the same torque as in the first tightening pass. These tests are designated by the CDCWNS label.

4.3.1.1 TEST RESULTS

A summary of the most pertinent fastener tension results for the CDCWNS series tests is shown in Tables 4.3 and 4.4. As noted above, the tests for the 3" and 4" grip lengths were two pass tests (tightening and touch-up). Table 4.3 lists the results for the tightening passes and Table 4.4 shows those for the touch-up passes. Both tables include values of average final fastener tension, average initial fastener tension, and the average loss of tension for the fasteners of both the interior and exterior rows of the connection. The interior rows consisted of fasteners 4-9 and the exterior rows were made up of fasteners 1-3 and 10-12 (see Figure 4.1). The final fastener tensions refer to the loads in the bolts upon completion of the appropriate installation pass (either tightening or touch-up). The initial tensions are those measured in each fastener immediately after tensioning of that particular fastener for each type of installation pass. The tensile load loss is the difference between the initial and final tensions for each fastener during each installation pass. Standard deviations are listed for all quantities.

Test CDCWNS-2:

Figures 4.36 to 4.40 and Tables 4.3 to 4.4 present the results of this 2" grip test. As noted in Figure 4.36, the average final installed fastener tension was 39.8 kips, just slightly above the 39 kip minimum. Although the middle plate was deflected 3mm, it appeared that subsequent fastener tightening had little effect on the installed fastener tensile loads (see Figures 4.38, 4.39, and 4.40). Table 4.3 shows that the average tension loss was 1.8 kips for the interior fasteners and 0.8 kips for the exterior fasteners. The calibrated wrench tightening method produced fairly uniform loads in the connection fasteners as evidenced by the 1.1 kip standard deviation in the initial tight tensions of the bolts (Table 4.3). No touch-up pass was conducted for the 2" grip connection test and therefore no results for this test are listed in Table 4.4.

Test CDCWNS-3:

The results of this 3" grip test are shown in Figures 4.41 through 4.45 and in Tables 4.3 and 4.4. The average bolt tension after the first pass of tightening was 31.8 kips and the average final installed tension (after touch-up) was 36.1 kips, as shown in Figure 4.41. Both values were

Test #	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in Interior Rows	Standard Deviation	Average Tension Loss in Exterior Rows	Standard Deviation
CDCWNS-2	39.8	1.6	41.0	1.1	1.8	0.9	0.8	0.4
CDCWNS-3	31.8	4.9	36.4	2.2	8.4	1.0	0.9	0.6
CDCWNS-4	27.3	11.3	40.0	2.8	21.8	5.4	4.2	1.8

Note: All values in Kips

Table 4.3: Summary of fastener load results for CDCWNS series tests - tightening pass

Test #	Average Final Touch-up Fastener Tension	Standard Deviation	Average Initial Touch-up Fastener Tension	Standard Deviation	Average Tension Loss in Interior Rows	Standard Deviation	Average Tension Loss in Exterior Rows	Standard Deviation
CDCWNS-2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CDCWNS-3	36.1	2.3	36.3	2.2	0.4	0.2	0.1	0.1
CDCWNS-4	38.0	3.1	38.7	2.9	1.3	0.7	0.1	0.1

Note: All values in Kips

Table 4.4: Summary of fastener load results for CDCWNS series tests - touch-up pass

less than the specified minimum allowable preload. Table 4.3 shows that during the tightening pass, tensile losses in the installed fasteners of the interior rows were large (8.4 kips on average) in comparison to those observed in the previous 2" grip and flat plate tests. These interior fasteners are located in the most deformed part of the connection. The bolts in the outer rows of the splice exhibited lesser tension losses, on the order of about 1 kip on average. During the touch-up pass, loss of tension in both the interior and exterior fasteners was, on average, below 0.5 kips.

During both the tightening and touch-up of the connection fasteners, varying magnitudes of initial tension were developed in the fasteners with the calibrated torque wrench. These initial tensions were consistently below 39 kips. Tables 4.3 and 4.4 show that the standard deviations in initial individual fastener tensions for both passes was 2.2 kips. The maximum variation in initial load between bolts was 8 kips for the tightening pass and 7.6 kips for the touch-up pass.

Test CDCWNS-4:

Figures 4.46 to 4.50 and Tables 4.3 and 4.4 present the results of this connection plate test. As in the 3" grip test, a touch-up pass was executed after the initial bolt tightening pass. During the tightening sequence, tensile load losses were large in the interior fasteners of the connection and averaged about 21.8 kips. The magnitudes of the preload losses in the exterior fasteners also increased over the 3" grip results to an average of about 4.2 kips. During the touch-up pass, some loss of load occurred in all fasteners, but not nearly of the same magnitudes experienced during tightening. The final average installed tension for the connection fasteners (after touch-up) was 38 kips which was higher than the result of the 3" grip test but still below the 39 kip required minimum.

The initial tensions developed in the bolts by the torque wrench during both installation passes varied widely. For both the tightening and touch-up sequences, the standard deviations of the initial fastener tensions were 2.8 and 2.9 kips, respectively (see Tables 4.3 and 4.4). The maximum variation in applied load between individual fasteners was 9.7 kips for the tightening pass and 10.7 kips for the touch-up pass.

4.3.2 CALIBRATED WRENCH (w/SNUGGING) INSTALLATION METHOD

These calibrated wrench tests were performed with a snugging pass that was intended to introduce an initial snug load of about 12 kips into each fastener of the connection. A second installation pass to "tighten" the bolts to 41 kips (39 kips + 5%) was then undertaken. As the

Fastener Number

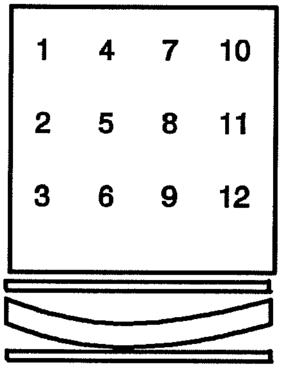
Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	40.9	-0	-0	-0	0.0	0.1	-0	0.0	0	-0	0	0.3
5.0	39.9	42.1	0.1	0.1	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.3
6.0	39.7	41.0	41.8	0.1	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.2
7.0	39.6	40.8	40.9	40.1	0.0	0.2	-0	-0	0	0.1	-0.1	-0
8.0	39.7	40.9	40.7	37.7	39.8	0.1	-0.1	-0.1	0	0	-0.1	-0.1
9.0	39.8	41.0	40.3	37.6	38.1	40.8	0.1	0	0.2	0.1	0.1	0
1.0	40.1	40.6	40.0	37.3	37.7	39.6	39.7	0	0	0.0	0.0	0.0
2.0	40.1	40.8	40.0	37.3	37.7	39.5	39.3	39.4	0.1	0	0.1	0.1
3.0	40.2	40.9	40.5	37.4	37.8	39.6	39.2	38.9	42.5	0	0.1	0.1
10.0	40.0	40.8	40.5	37.0	37.6	39.5	39.1	38.7	42.1	40.4	0	-0
11.0	40.0	41.0	40.6	36.7	37.7	39.6	39.1	38.4	41.5	40.3	42.2	0
12.0	39.8	40.9	40.4	36.6	37.5	39.6	38.9	38.3	41.3	40.2	41.7	41.9

Tension in Kips

Average Fastener Tension = 39.8 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates
Cal. Wrench Installation
(w/o Snugging)



Fastener Numbers

Figure 4.36: Fastener Tensions for Test CDCWNS-2

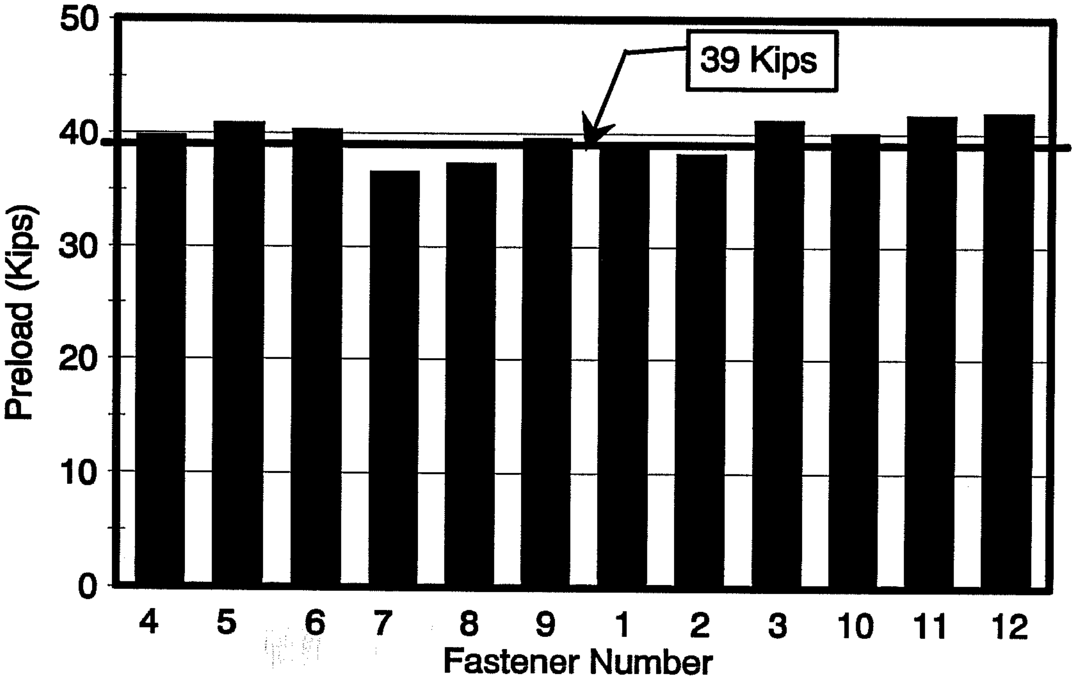


Figure 4.37: Final Installed Tensions for Test CDCWNS-2

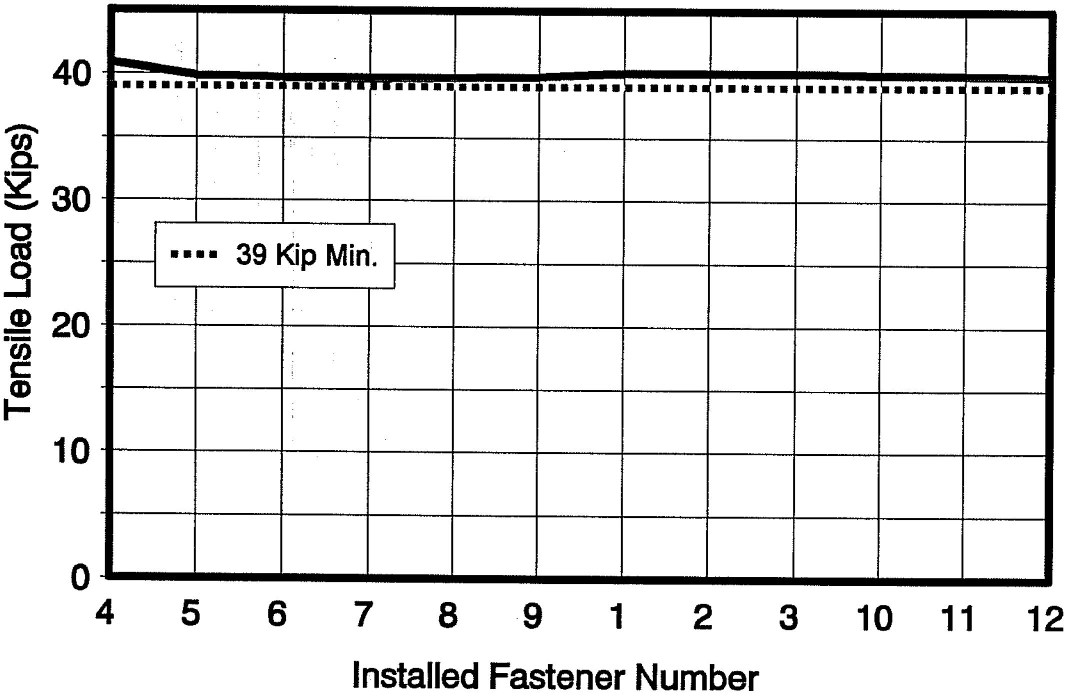


Figure 4.38: Tensile Load History for Fastener #4 - Test CDCWNS-2

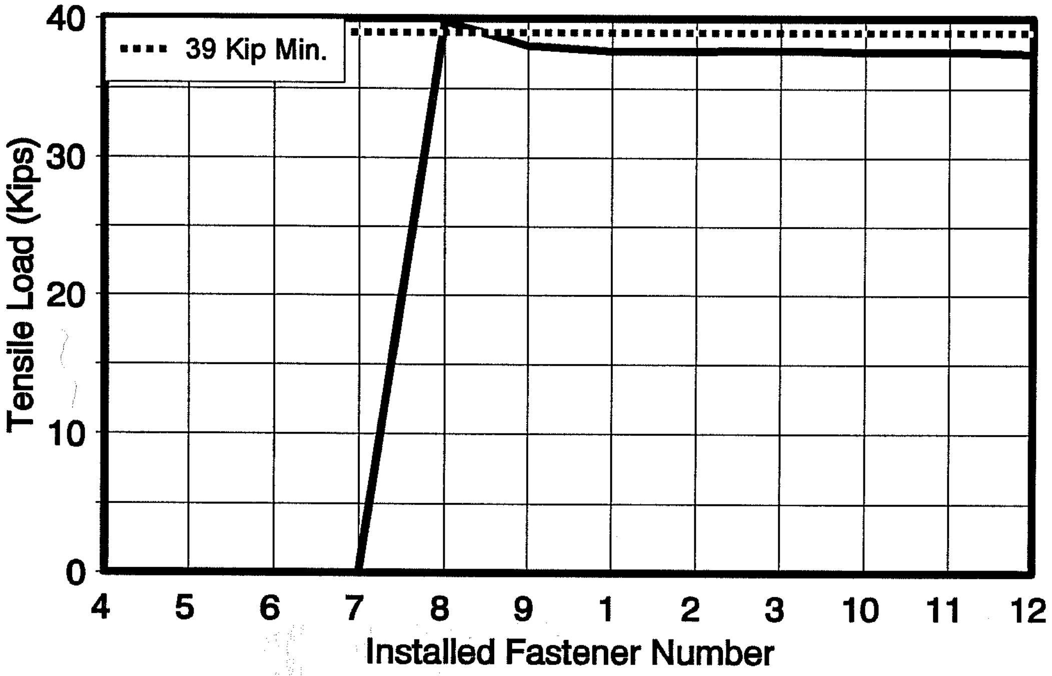


Figure 4.39: Tensile Load History for Fastener #8 - Test CDCWNS-2

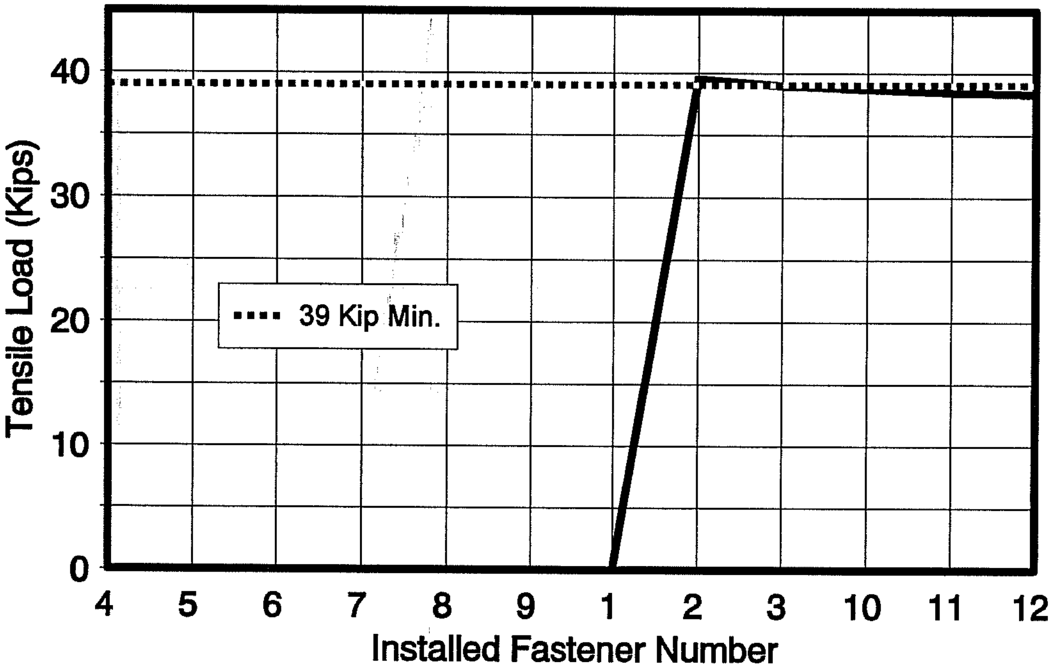


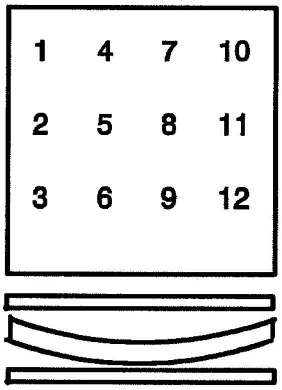
Figure 4.40: Tensile Load History for Fastener #2 - Test CDCWNS-2

Fastener Number

		4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
Tightening Order	4.0	37.5	0	0	-0	0.1	0	0	-0	-0	0	-0	0.3
	5.0	27.7	34.9	-0	-0.1	-0.1	0	-0	0.1	0.0	0	-0.1	-0
	6.0	27.8	26.2	32.2	-0.2	0	0.1	-0.1	-0	-0.1	-0.1	-0.1	-0
	7.0	28.1	26.3	31.7	39.0	0.1	0.1	-0	-0	-0.1	-0.1	-0.1	0
	8.0	28.9	26.1	31.3	31.7	37.3	-0.1	-0.2	-0.1	-0.3	-0.3	-0.3	-0.1
	9.0	29.1	27.7	29.9	31.2	30.9	33.2	-0.1	0.1	-0.2	-0.1	-0.3	-0
	1.0	28.1	26.1	28.0	31.5	31.0	33.0	36.9	0	-0.1	-0.1	0.1	0.1
	2.0	28.4	25.8	25.0	31.3	30.9	33.3	35.3	36.4	-0.2	-0.1	-0	-0
	3.0	28.4	26.5	23.3	31.5	31.0	34.1	35.5	34.9	37.6	-0	0	-0
	10.0	28.5	26.5	23.5	29.0	28.8	32.3	35.5	34.9	37.1	35.4	-0	0
	11.0	28.5	26.6	23.7	29.3	28.0	29.4	35.4	34.9	36.8	35.2	35.8	-0
	12.0	28.5	26.6	23.9	29.5	28.4	26.9	35.5	34.8	37.0	35.2	35.4	40.2
Touch-up Pass	4.0	35.3	26.5	23.9	29.4	28.6	27.0	35.4	34.7	36.7	35.0	35.1	39.8
	5.0	35.1	33.4	23.8	29.3	28.4	27.1	35.4	34.6	36.7	34.9	35.1	39.7
	6.0	35.1	33.3	32.2	29.3	28.3	26.7	35.4	34.8	36.7	35.0	35.1	39.7
	7.0	35.0	33.3	32.1	39.8	28.5	26.7	35.4	34.7	36.8	35.0	35.2	39.7
	8.0	34.9	33.2	32.1	39.7	37.8	26.7	35.4	34.7	36.7	35.0	35.1	39.7
	9.0	34.9	33.2	31.5	39.5	37.8	35.4	35.4	34.6	36.6	34.9	35.1	39.7
	1.0	34.8	33.1	31.5	39.5	37.6	35.2	36.5	34.7	36.8	35.0	35.1	39.7
	2.0	35.0	33.1	31.6	39.5	37.8	35.1	36.5	36.9	36.7	35.0	35.1	39.7
	3.0	34.8	33.1	31.5	39.5	37.6	35.1	36.5	36.9	37.2	35.0	35.1	39.7
	10.0	34.8	33.1	31.4	39.3	37.6	35.1	36.4	36.7	37.1	35.9	35.0	39.6
	11.0	34.9	33.1	31.5	39.4	37.7	35.1	36.4	36.7	37.2	36.0	35.9	39.7
	12.0	34.9	33.1	31.5	39.4	37.6	35.0	36.4	36.7	37.2	35.9	35.9	39.8

Tension in Kips

Average Fastener Tension = 31.8 Kips
(after tightening)
Average Fastener Tension = 36.1 Kips
(after touch-up)
4-1/4" Conventional Fasteners
3" Grip
Deformed Plates
Cal. Wrench Installation (w/o Snugging)
(Touch-up Pass)



Fastener Numbers

Figure 4.41: Fastener Tensions for Test CDCWNS-3

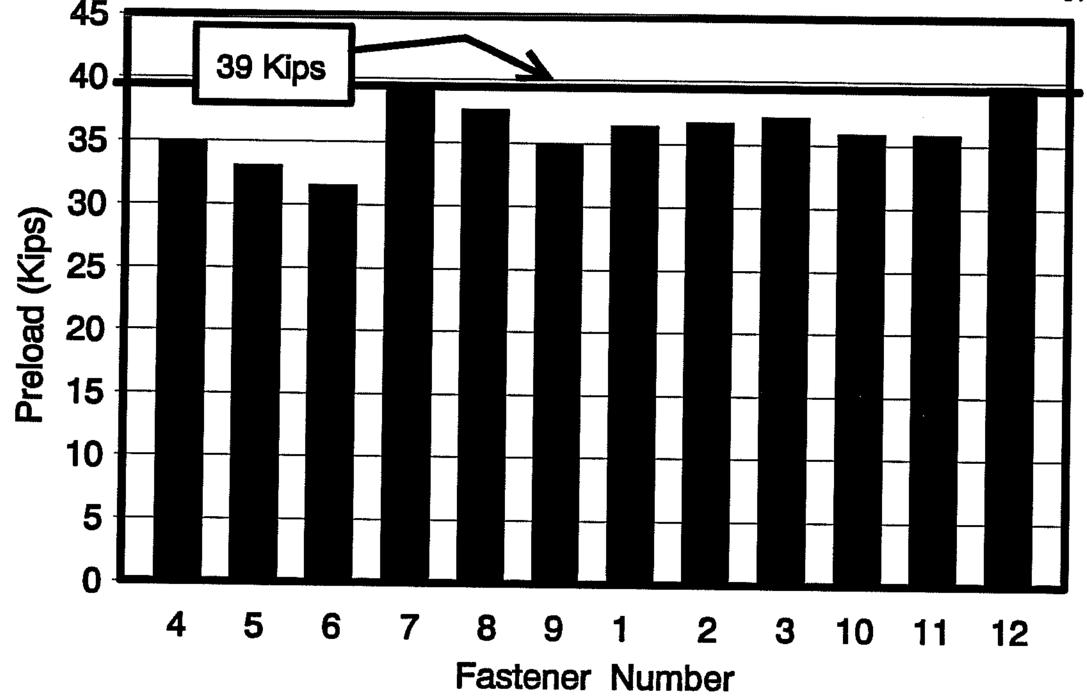


Figure 4.42: Final Installed Tensions for Test CDCWNS-3

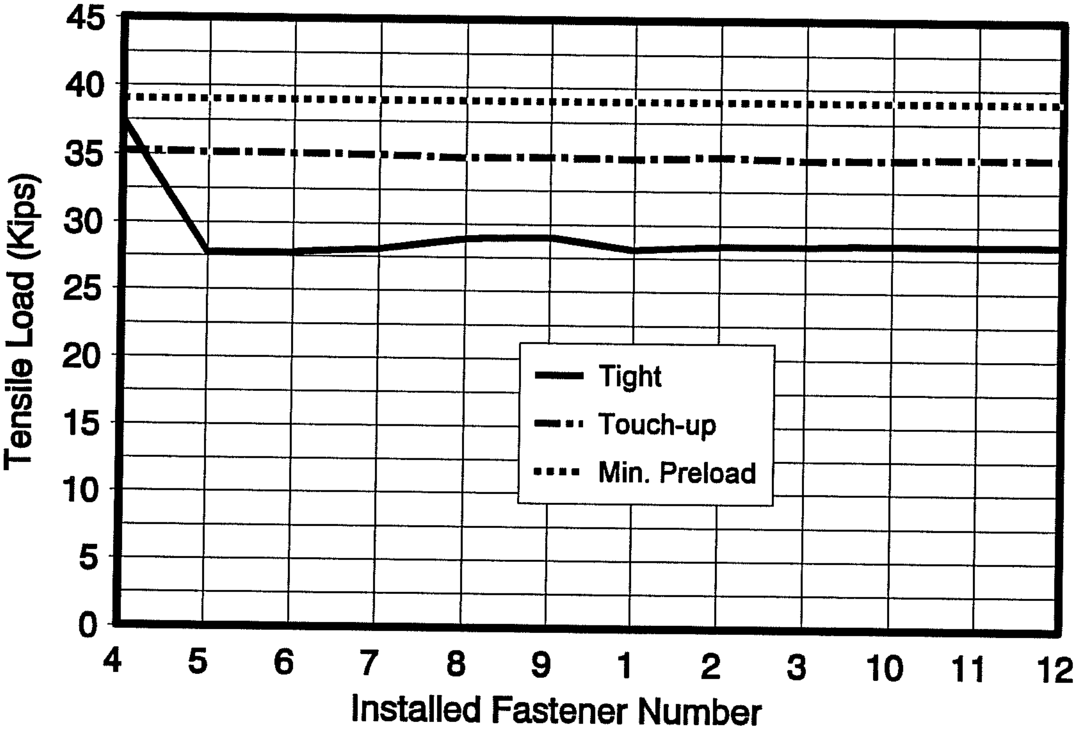


Figure 4.43: Tensile Load History for Fastener #4 - Test CDCWNS-3

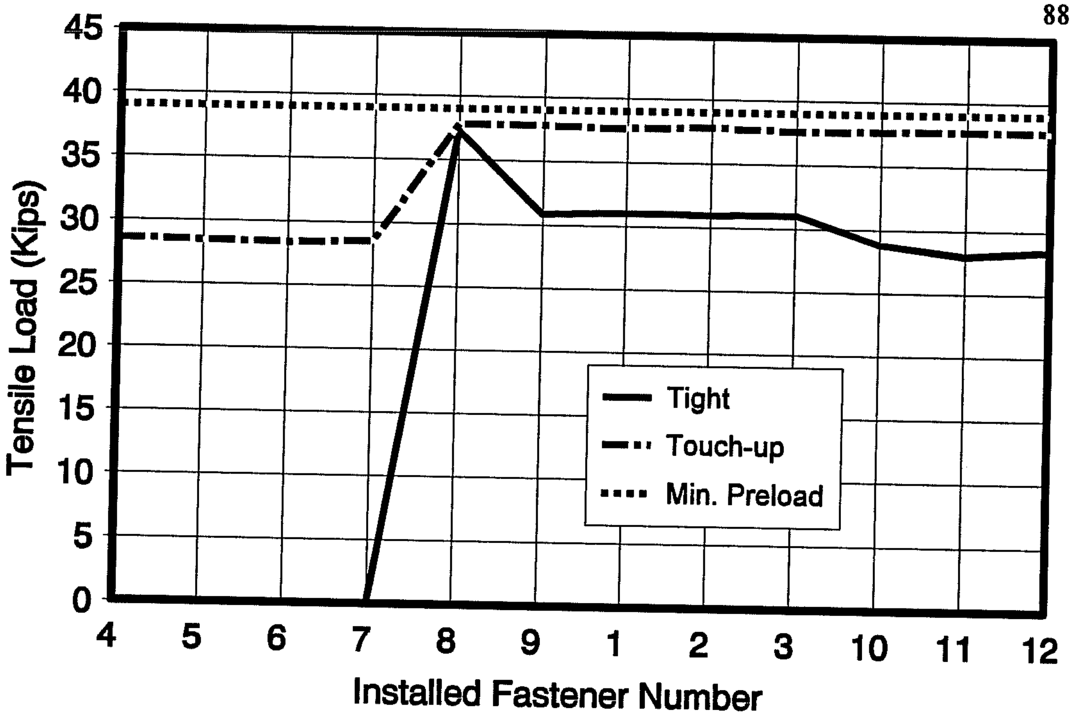


Figure 4.44: Tensile Load History for Fastener #8 - Test CDCWNS-3

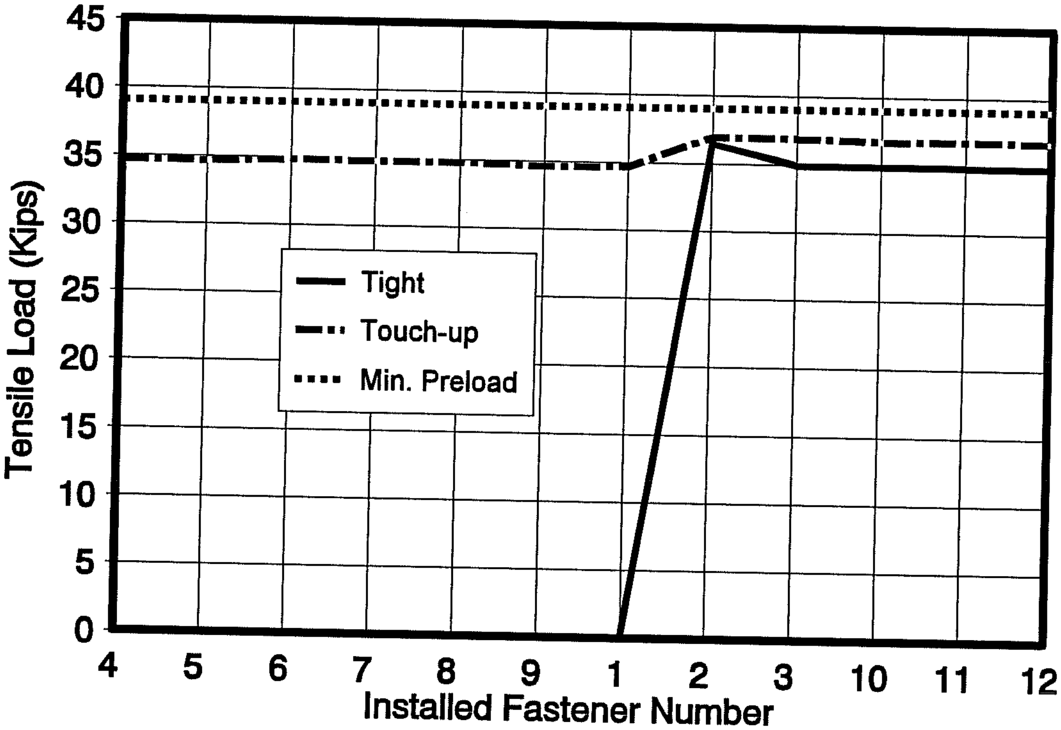


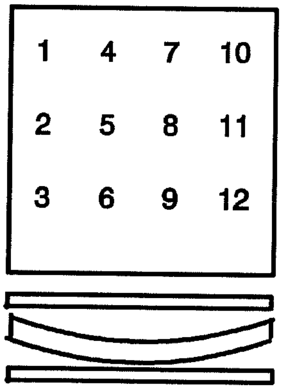
Figure 4.45: Tensile Load History for Fastener #2 - Test CDCWNS-3

Fastener Number

		4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
Tightening Order	4.0	37.8	-0.2	-0	0.0	-0	-0	-0.1	-0.1	-0	1.1	1.0	1.2
	5.0	15.8	37.6	-0	-0	-0	-0	-0	-0.1	-0	1.4	0.8	0.2
	6.0	15.4	18.4	40.1	-0	-0	-0.1	-0	-0.1	-0.1	1.3	0.3	-0.1
	7.0	14.7	17.8	38.7	37.1	-0	-0.1	-0	-0	-0.1	-0	-0.1	-0.1
	8.0	19.5	20.4	40.4	23.1	41.2	-0	-0	-0	-0	-0	-0	-0
	9.0	21.7	24.4	38.4	21.4	29.2	41.7	0	-0	-0	-0	0	0
	1.0	7.5	13.2	32.0	24.8	31.2	43.0	41.9	-0	-0	-0	0	0
	2.0	8.0	11.9	26.6	24.8	31.5	43.1	36.3	43.2	-0	-0	-0	0
	3.0	8.3	10.9	25.0	25.0	31.7	44.5	36.3	37.1	45.8	-0	-0	-0.1
	10.0	10.3	11.9	25.9	10.9	20.4	36.5	36.3	37.0	45.0	36.1	-0.1	-0
	11.0	10.5	12.2	26.6	11.8	16.5	29.0	36.3	37.0	44.9	31.4	37.6	-0.1
	12.0	10.5	12.2	26.7	11.9	17.1	26.4	36.3	37.0	44.8	31.5	33.8	39.0
Touch-up Pass	4.0	36.8	11.6	26.7	10.1	16.7	26.5	36.2	37.1	44.7	31.5	33.7	38.1
	5.0	36.2	35.7	26.5	10.1	15.9	26.4	36.2	37.0	44.7	31.4	33.7	38.0
	6.0	36.0	35.3	38.2	10.2	16.0	25.6	36.2	37.1	44.5	31.4	33.6	37.6
	7.0	34.3	35.1	38.2	37.7	15.1	25.7	36.3	37.1	44.5	31.1	33.6	37.5
	8.0	34.2	34.6	38.2	36.7	42.2	25.3	36.3	37.1	44.4	31.2	33.5	37.5
	9.0	34.3	34.5	37.2	36.6	41.5	41.0	36.3	37.2	44.5	31.2	33.6	37.5
	1.0	34.2	34.5	37.1	36.5	41.4	40.7	40.0	37.1	44.5	31.2	33.6	37.4
	2.0	34.3	34.5	37.1	36.5	41.4	40.7	39.9	37.9	44.5	31.2	33.6	37.4
	3.0	34.2	34.5	37.2	36.5	41.3	40.6	39.8	37.8	44.6	31.2	33.6	37.4
	10.0	34.2	34.4	37.1	36.4	41.3	40.5	39.8	37.7	44.6	33.9	33.5	37.3
	11.0	34.2	34.4	37.1	36.4	41.2	40.5	39.8	37.8	44.6	33.9	36.0	37.4
	12.0	34.2	34.4	37.1	36.4	41.2	40.5	39.7	37.7	44.6	33.9	36.0	39.8

Tension in Kips

Average Fastener Tension = 27.3 Kips
(after tightening)
Average Fastener Tension = 38.0 Kips
(after touch-up)
5-1/4" Conventional Fasteners
4" Grip
Deformed Plates
Cal. Wrench Installation (w/o Snugging)
(Touch-up Pass)



Fastener Numbers

Figure 4.46: Fastener Tensions for Test CDCWNS-4

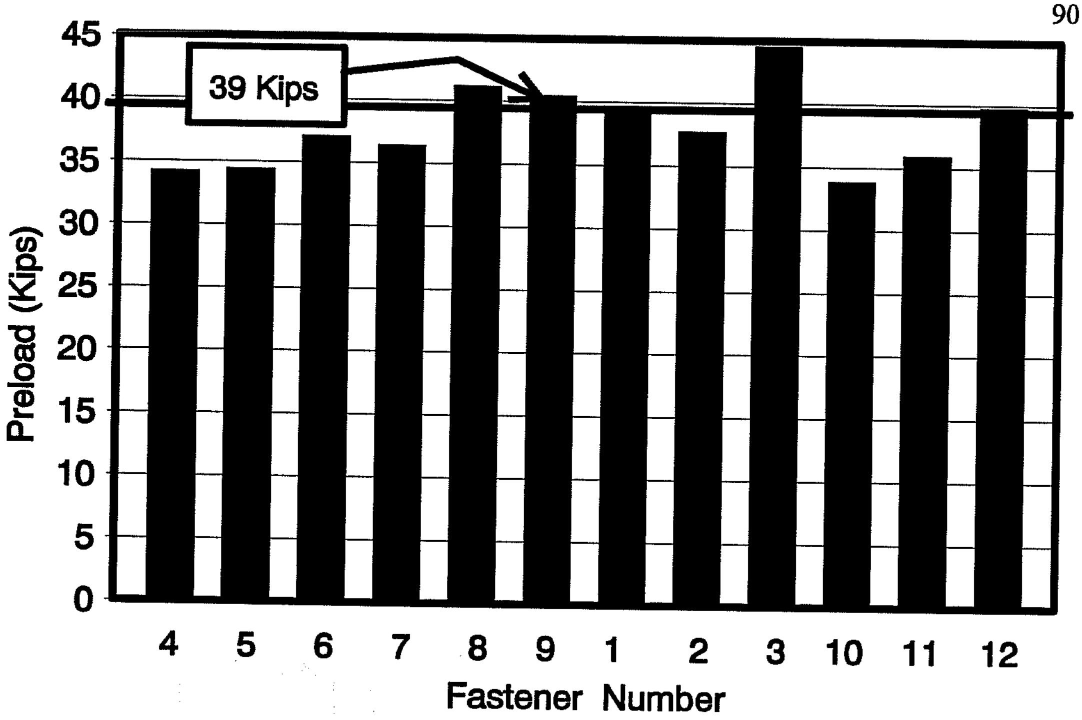


Figure 4.47: Final Installed Tensions for Test CDCWNS-4

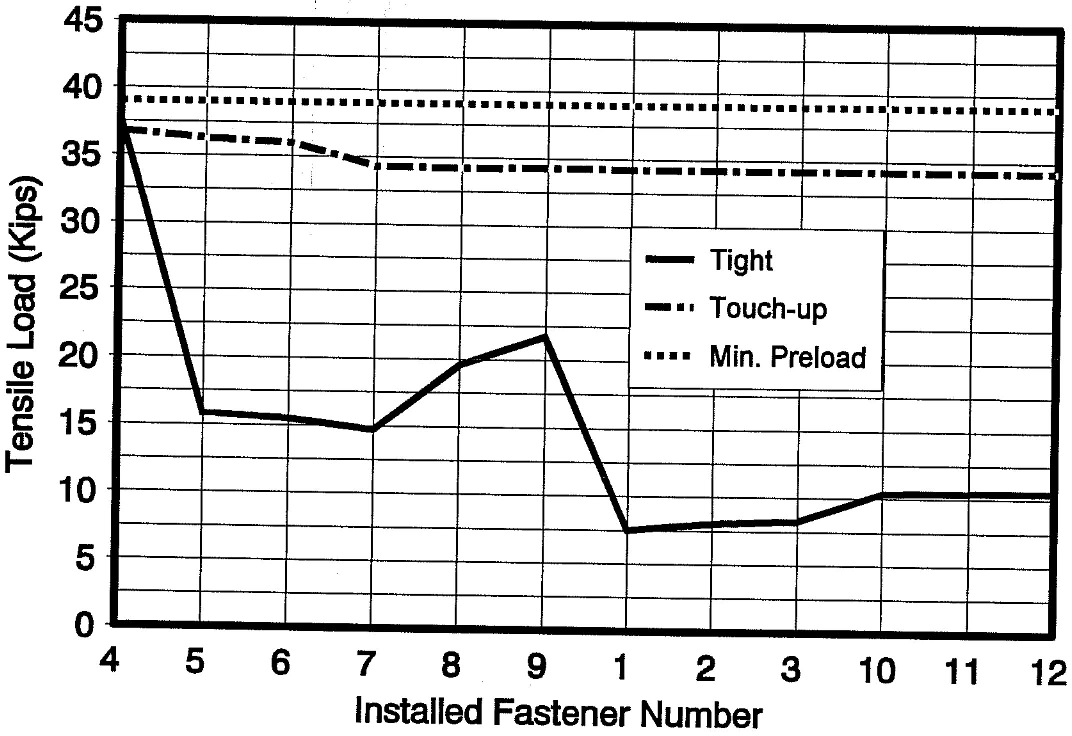


Figure 4.48: Tensile Load History for Fastener #4 - Test CDCWNS-4

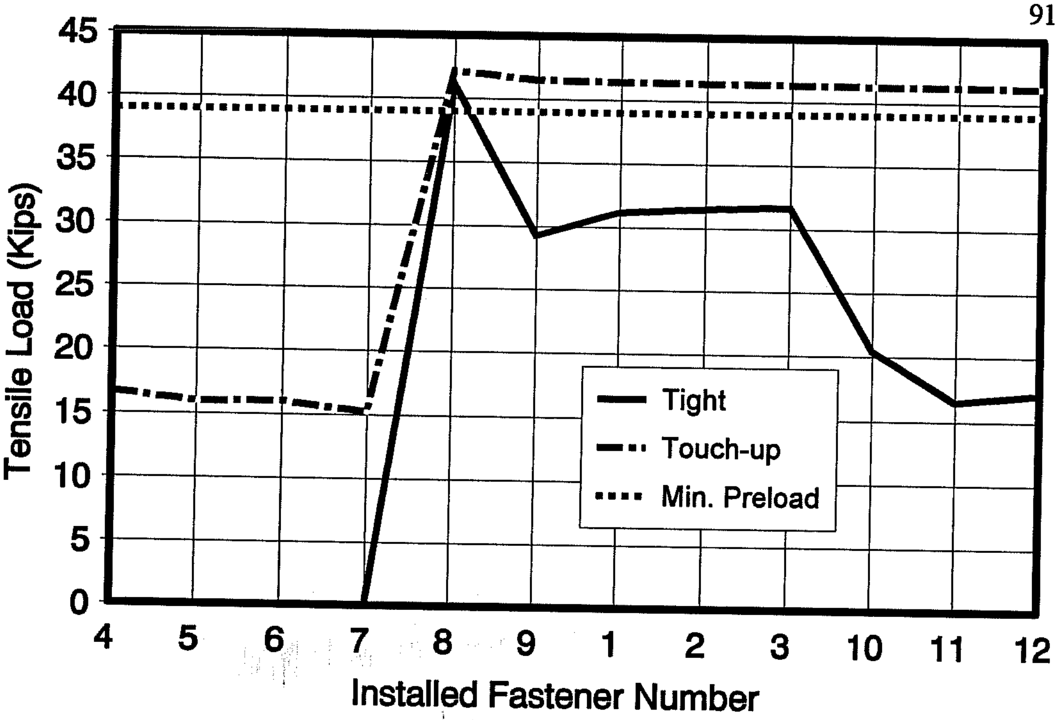


Figure 4.49: Tensile Load History for Fastener #8 - Test CDCWNS-4

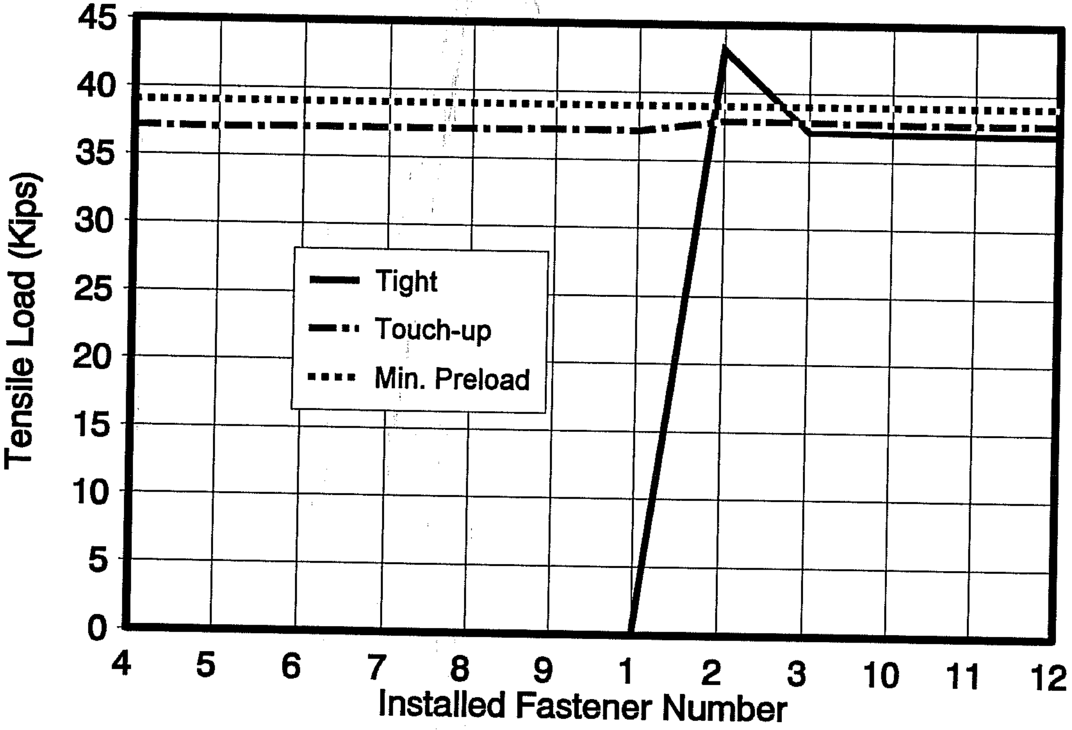


Figure 4.50: Tensile Load History for Fastener #2 - Test CDCWNS-4

snugging was done to produce a certain value of bolt tension, it did not explicitly follow the guidelines laid out in the *Bolt Specification*. The 12 kip snug load was selected to replicate the loads to which the Huck fasteners would be snugged to in the tests described in the next chapter. A basis for comparison of the performance of the two fasteners was thereby established. The snug loads (as well as the subsequent full tight loads in the tightening pass) were induced in the bolts by the use of a torque wrench which was set to a value of torque indicated by the torque-load relationships shown in Appendix A. As in the flat plate tests of Section 4.2.1, a few sample fasteners of each length were installed in the Skidmore-Wilhelm bolt tension indicator prior to testing to confirm the torque needed to produce the desired load value. A setting between 90-110 ft.*# was used for the 12 kip load and a range of 280-300 ft.*# was utilized for the full tight (39 kips+5%=41 kips) target load. These ranges of applied torque were adequate for all bolt lengths. For the 4" grip in this series of connection tests, an additional touch-up pass was conducted after tightening. The setting on the torque wrench was not altered from that used in the tightening pass.

The tests using this installation method and plate configuration were designated as the CDCW series.

4.3.2.1 TEST RESULTS

A list of the most pertinent fastener tension results for the CDCW series tests is shown in Tables 4.5, Table 4.6, and Table 4.7. As noted above, the test for the 4" grip length was a three pass installation (snugging, tightening, and touch-up). Table 4.5 lists the results for the snugging passes, Table 4.6 the results of the tightening passes, and Table 4.7 shows those for the touch-up passes. All tables include values of average final fastener tension, average initial fastener tension, and the average loss of tension for the fasteners of both the interior and exterior rows of the connection. The interior rows consisted of fasteners 4-9 and the exterior rows were made up of fasteners 1-3 and 10-12. The final fastener tensions refer to the loads in the bolts upon completion of the appropriate installation pass (snugging, tightening, or touch-up). The initial tensions are those measured in each fastener immediately after tensioning of that particular fastener during each installation pass. The tensile load loss is the difference between the initial and final tensions for each fastener during each installation pass. Standard deviations are listed for all quantities.

Test #	Average Final Snug Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Tension Loss in Interior Rows	Standard Deviation	Average Tension Loss in Exterior Rows	Standard Deviation
CDCW-2	7.8	3.6	11.0	0.9	5.4	2.6	0.8	0.9
CDCW-3	3.8	3.5	9.5	0.8	8.2	1.1	3.9	3.7
CDCW-4	4.3	4.6	10.7	1.0	9.3	1.2	4.4	4.5

Note: All values in Kips

Table 4.5: Summary of fastener load results for CDCW series tests - snugging pass

Test #	Average Final Tight Fastener Tension	Standard Deviation	Average Initial Tight Fastener Tension	Standard Deviation	Average Tension Loss in Interior Rows	Standard Deviation	Average Tension Loss in Exterior Rows	Standard Deviation
CDCW-2	39.5	3.0	40.1	3.1	0.8	0.2	0.5	0.2
CDCW-3	35.4	4.3	37.2	2.8	3.6	1.8	0.1	0.2
CDCW-4	30.4	9.4	40.5	1.9	18.0	3.8	2.6	1.2

Note: All values in Kips

Table 4.6: Summary of fastener load results for CDCW series tests - tightening pass

Test #	Average Final Touch-up Fastener Tension	Standard Deviation	Average Initial Touch-up Fastener Tension	Standard Deviation	Average Tension Loss in Interior Rows	Standard Deviation	Average Tension Loss in Exterior Rows	Standard Deviation
CDCW-2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CDCW-3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CDCW-4	38.8	2.7	39.2	2.5	0.9	0.4	0.1	0.1

Note: All values in Kips

Table 4.7: Summary of fastener load results for CDCW series tests - touch-up pass

Test CDCW-2:

Figures 4.51 to 4.55 and Tables 4.5 through 4.7 show the results of this 2" grip connection plate test. The symbol "B.G." in Figure 4.51 indicates that the BTM gauge installed in fastener 7 gave faulty strain readings upon tightening of the fastener and was determined to have become unusable. This notation is used in the presentation of the results of the remainder of the tests in this report. After the tightening pass was completed, the remaining eleven bolts showed an average tensile load of 39.5 kips. Tensile load losses in the fasteners during both installation passes (snugging and tightening) were greatest in the interior rows of bolts, especially for the snugging pass. The average preload loss in those fasteners during snugging was 5.4 kips while the exterior bolts exhibited an average loss of 0.8 kips. For the tightening pass, tension relaxation in both the interior and exterior regions of the connection was at an average value of less than 1 kip. Figures 4.53 to 4.55 show the load histories of fasteners 4, 8, and 2 which illustrate the aforementioned preload losses.

For the snugging pass, the initial tensions induced by the torque wrench for each fastener were fairly consistent with a standard deviation from the mean value of only 0.9 kips. For the tightening pass, however, this figure jumped to 3.1 kips which indicated a wide variation in the initial loads. The maximum difference in the initial tensions during the tightening pass was 12 kips between fastener 1 and fastener 4.

Test CDCW-3:

The results of this test are shown in Figures 4.56 through 4.60 and Tables 4.5 to 4.7. Per Figure 4.56, the final average tension in each fastener after tightening was 35.4 kips, well below the 39 kip minimum preload. During the snugging pass, tensile load loss in both the interior and exterior rows of bolts was much greater than in any other previous test. The average loss for the interior fasteners was 8.2 kips while the exterior fasteners exhibited an average relaxation of 3.9 kips (see Table 4.5). When the fasteners were tightened, tension loss in the interior bolts remained high (average= 3.6 kips) but the exterior rows lost almost no load as evidenced by the average reduction of only 0.1 kips. Figures 4.58 through 4.60 illustrate these preload losses for fasteners 4, 8, and 2, of which 4 and 8 are interior fasteners and 2 is an exterior fastener.

The calibrated torque wrench induced fairly uniform values of load in the connection fasteners during the snugging pass. Table 4.5 records the relatively low standard deviation in these values of 0.8 kips. The maximum variation in initial individual bolt snug loads was 2.6 kips. During tightening, the standard deviation grew to 2.8 kips, indicating fairly erratic values of initial "tight" fastener tensions. For the tightening pass, the largest variation in the initial "tight" bolt tensions was 10.1 kips.

Test CDCW-4:

Figures 4.61 to 4.65 and Tables 4.5 to 4.7 detail the results of this 4" grip test with an additional touch-up pass. During the overall installation sequence, preload losses occurred in all fasteners, with the largest losses developing in the interior bolts of the connection. This tensile load relaxation was greatest during the tightening pass during which the average loss was 18 kips (see Table 4.6). The greatest loss in tension for the exterior fasteners was during the snugging pass in which the average loss was 4.4 kips. Figures 4.63, 4.64, and 4.65 illustrate the varying tensile loads for fasteners 4, 8, and 2. After touch-up was completed, the average fastener tension was 38.8 kips, which is very close to the required 39 kip value.

The initial loads induced in the fasteners during the snugging pass were fairly consistent with a standard deviation from the mean of only 1 kip as shown in Table 4.5. For the tightening and touch-up passes, however, the standard deviations were much higher; they changed to 1.9 and 2.5 kips, respectively. During tightening, the maximum variation in initial applied load between individual fasteners was 7.1 kips while during touch-up the largest difference was 8.9 kips.

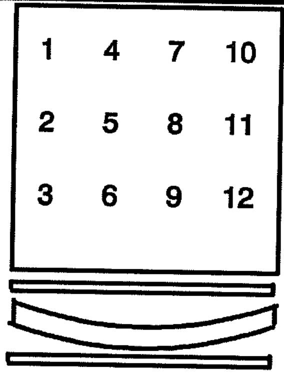
Fastener Number

		4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
Snugging Order	4.0	8.8	0	0	0	0	-0	0	-0	0	0	0.1	0.2
	5.0	2.2	10.9	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.1
	6.0	3.0	5.1	10.7	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.2	0.1
	7.0	2.2	5.4	11.4	10.9	0.2	-0	0.1	0	0.1	0	-0	0.1
	8.0	2.5	4.6	11.1	6.3	11.3	-0	0	-0	0.1	-0	-0	0
	9.0	2.8	5.1	8.8	6.4	7.6	11.9	0.1	0.1	0.2	0.1	0.1	0.1
	1.0	0.3	2.4	7.5	7.2	8.0	11.8	12.5	0	0.1	0.1	0.1	0.1
	2.0	0.5	1.9	5.7	7.2	8.2	12.2	10.5	10.7	0.2	0	0.1	0.1
	3.0	0.4	2.2	5.3	7.1	8.1	12.4	10.5	9.2	10.8	0	0	0
	10.0	1.0	2.5	5.6	4.2	6.9	11.9	10.4	9.2	10.6	11.5	0	0
	11.0	0.9	2.6	5.8	4.5	6.8	11.3	10.4	9.2	10.5	11.8	10.5	0
	12.0	0.9	2.6	5.9	4.5	7.2	11.1	10.4	9.2	10.5	11.7	10.4	11.5
Tightening Order	4.0	32.7	1.7	6.0	2.5	6.3	11.3	11.6	9.5	10.4	11.7	10.2	11.2
	5.0	32.3	38.6	5.5	2.5	5.3	11.0	11.6	10.1	10.3	11.6	10.2	11.1
	6.0	32.1	38.3	41.8	2.5	5.5	9.3	11.6	10.1	11.1	11.6	10.1	11.1
	7.0	32.2	38.2	41.4	B.G.	5.2	9.4	11.5	10.1	11.0	11.9	10.2	11.0
	8.0	32.2	38.3	41.3	B.G.	42.1	9.3	11.5	10.0	11.0	12.0	10.5	11.1
	9.0	32.1	38.3	41.1	B.G.	41.7	41.7	11.5	10.0	11.0	11.9	10.5	11.4
	1.0	32.1	38.2	41.1	B.G.	41.5	41.4	44.7	10.2	11.0	11.9	10.5	11.4
	2.0	32.1	38.3	41.0	B.G.	41.4	41.3	44.3	37.9	11.4	11.9	10.5	11.4
	3.0	32.1	38.2	41.0	B.G.	41.3	41.2	44.1	37.7	42.7	11.9	10.5	11.4
	10.0	32.0	38.2	40.9	B.G.	41.2	41.0	44.0	37.6	42.4	38.4	10.7	11.3
	11.0	32.1	38.2	40.9	B.G.	41.2	41.0	44.0	37.5	42.4	38.1	40.5	11.6
	12.0	32.0	38.1	40.9	B.G.	41.2	41.0	43.9	37.5	42.3	37.9	40.3	39.7

Tension in Kips

Average Fastener Tension = 39.5 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates
Cal. Wrench Installation
(w/Snugging Pass)



Fastener Numbers

Figure 4.51: Fastener Tensions for Test CDCW-2

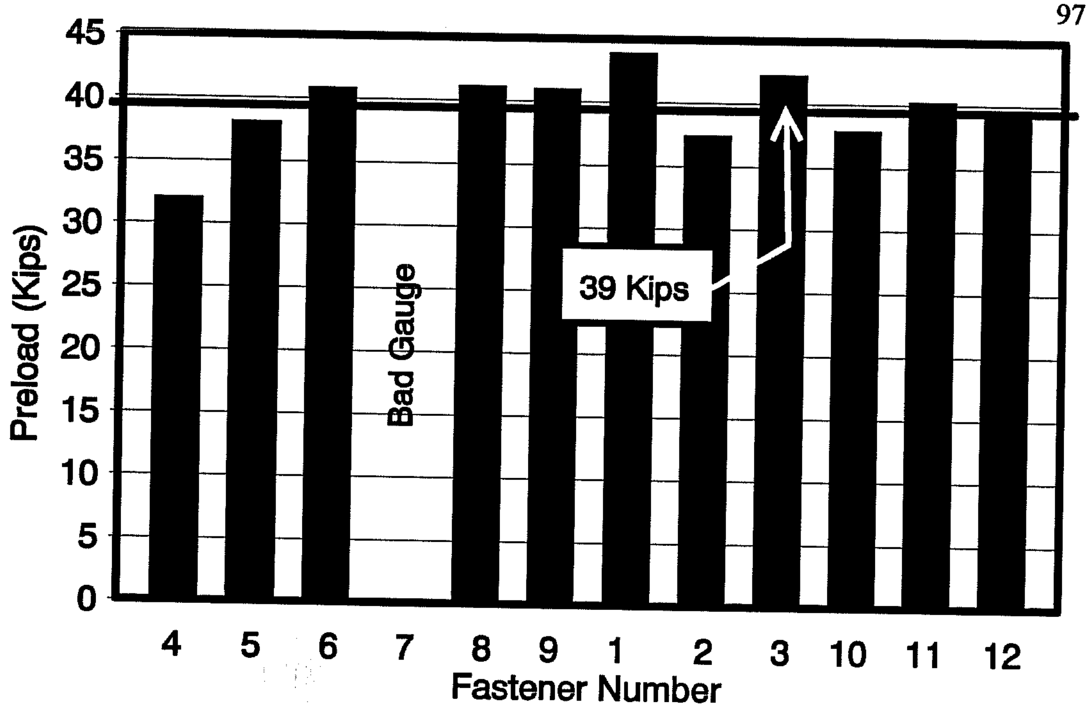


Figure 4.52: Final Installed Tensions for Test CDCW-2

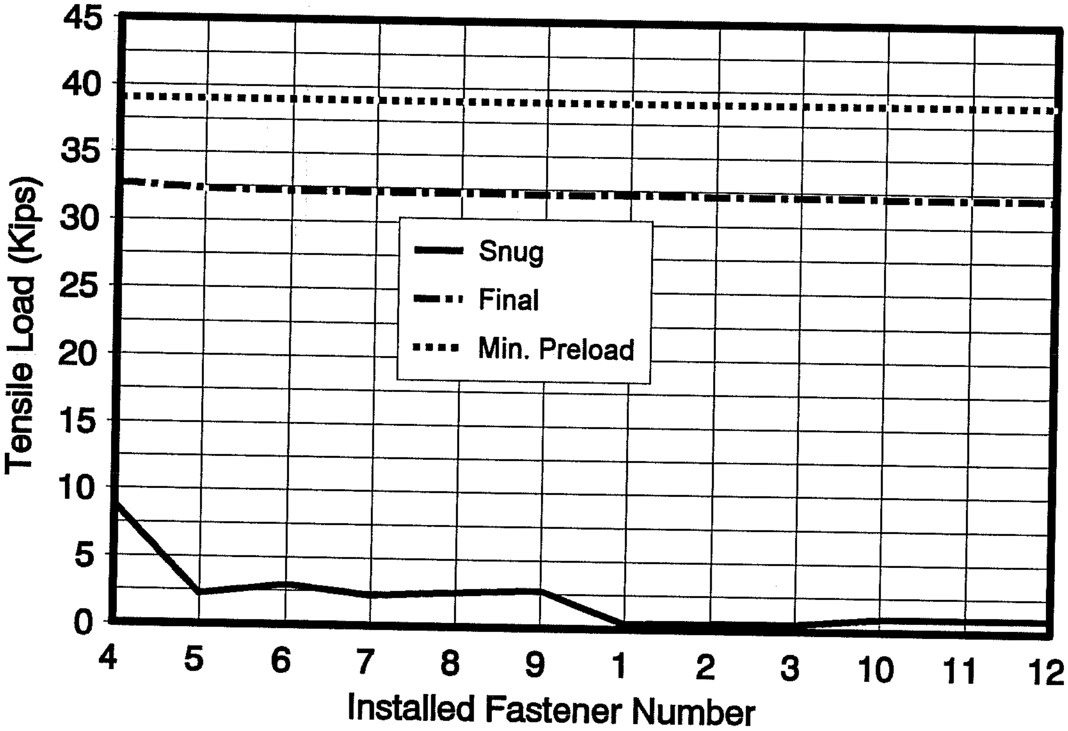


Figure 4.53: Tensile Load History for Fastener #4 - Test CDCW-2

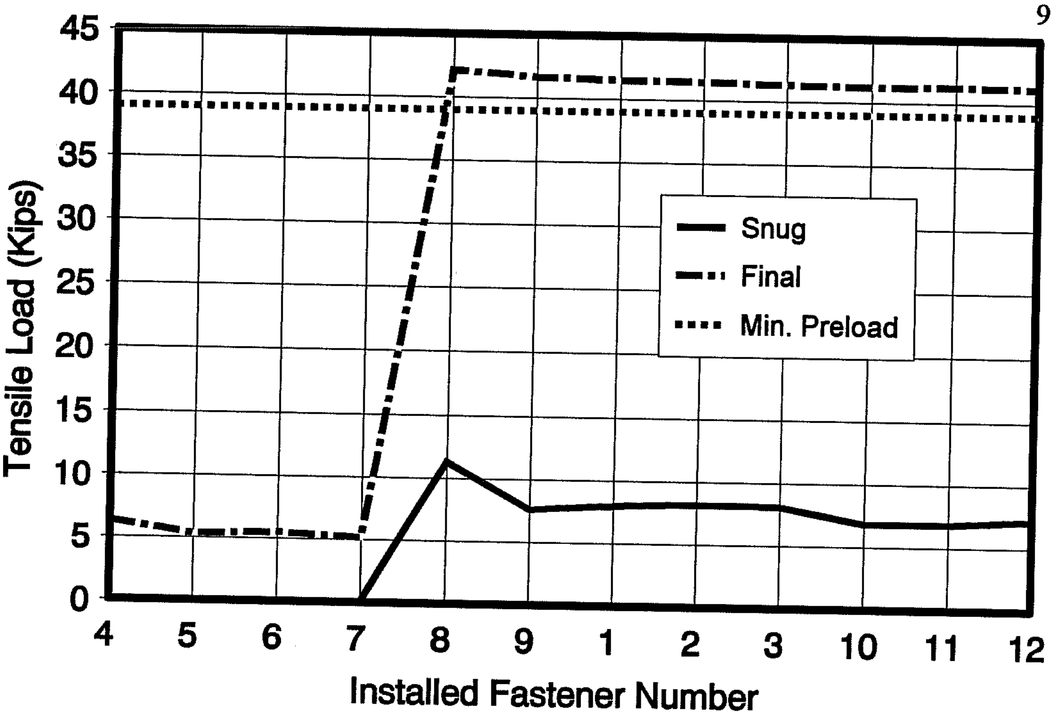


Figure 4.54: Tensile Load History for Fastener #8 - Test CDCW-2

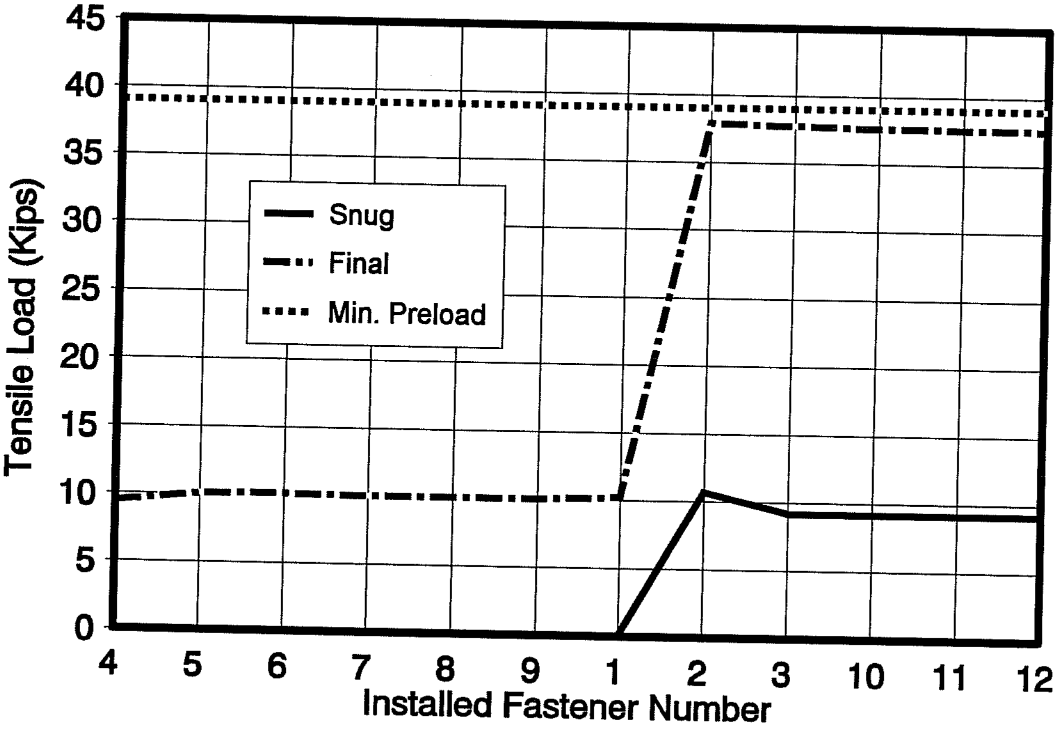


Figure 4.55: Tensile Load History for Fastener #2 - Test CDCW-2

Fastener Number

		4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
Snugging Order	4.0	9.6	0	0.1	0	0	0	0	0	0	0.4	0	0.1
	5.0	4.4	8.5	0	0.1	0.2	0.1	0	-0	0.1	0.3	0.1	0.1
	6.0	4.6	2.8	9.8	0	0.2	0.1	0	-0.1	0	0.4	0.1	0.1
	7.0	0.6	1.0	8.8	9.8	-0	-0	-0.1	-0.1	-0.1	-0.2	-0.1	-0.1
	8.0	0.9	0.7	6.5	5.2	8.6	0	0	0	0	-0	-0	0
	9.0	1.4	1.1	4.0	5.3	2.5	10.5	-0	0	-0.1	-0.1	-0.1	0
	1.0	0	0	0.8	6.7	3.3	12.1	10.1	-0	-0	-0.1	0	0
	2.0	0	0	0.1	7.3	3.3	12.2	3.5	9.5	0.1	0	0	0
	3.0	0	0	0	7.3	3.6	12.0	4.1	2.6	8.5	-0	-0	0.1
	10.0	0.1	-0	-0	1.0	1.7	11.3	5.2	3.1	9.7	9.3	0	0
	11.0	0.1	0	-0	1.6	0.9	8.1	5.4	3.3	10.8	3.6	11.1	0
	12.0	0.3	0	0	2.3	1.1	4.0	5.4	3.4	11.8	4.0	4.5	9.2
Tightening Order	4.0	34.5	0	-0	0	0.1	2.0	3.2	2.2	10.8	4.3	3.7	9.1
	5.0	31.5	31.8	0	-0.1	-0	0	4.0	1.5	8.2	4.7	3.2	8.3
	6.0	31.8	26.5	36.8	0.1	0.1	0	4.3	2.2	3.8	4.9	4.0	6.4
	7.0	30.1	26.1	36.2	41.9	-0	0	4.4	2.3	3.9	0.9	2.5	6.7
	8.0	30.4	25.0	35.2	41.2	33.8	0	4.4	2.3	4.1	0.7	1.1	5.0
	9.0	30.4	25.3	31.4	41.0	31.9	41.1	4.5	2.3	4.6	0.9	0.8	1.2
	1.0	30.7	25.7	31.7	40.8	31.7	40.3	39.3	0.6	4.0	0.9	0.8	1.3
	2.0	31.0	25.5	31.4	40.9	31.8	40.4	39.4	37.3	1.3	1.0	0.9	1.4
	3.0	31.0	26.0	30.6	40.9	31.7	40.5	39.3	37.6	36.4	1.0	1.0	1.5
	10.0	30.9	25.9	30.7	40.2	31.3	40.6	39.1	37.5	35.8	38.4	-0	1.2
	11.0	30.9	26.0	30.7	40.4	30.9	39.7	39.1	37.5	35.8	38.3	38.0	0.2
	12.0	31.0	26.0	30.8	40.6	31.3	38.7	39.2	37.4	36.0	38.2	38.0	37.6

Tension in Kips

Average Fastener Tension = 35.4 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates
Cal. Wrench Installation
(w/Snugging Pass)

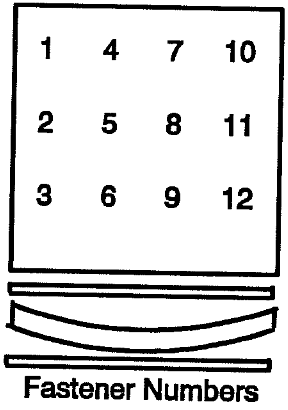


Figure 4.56: Fastener Tensions for Test CDCW-3

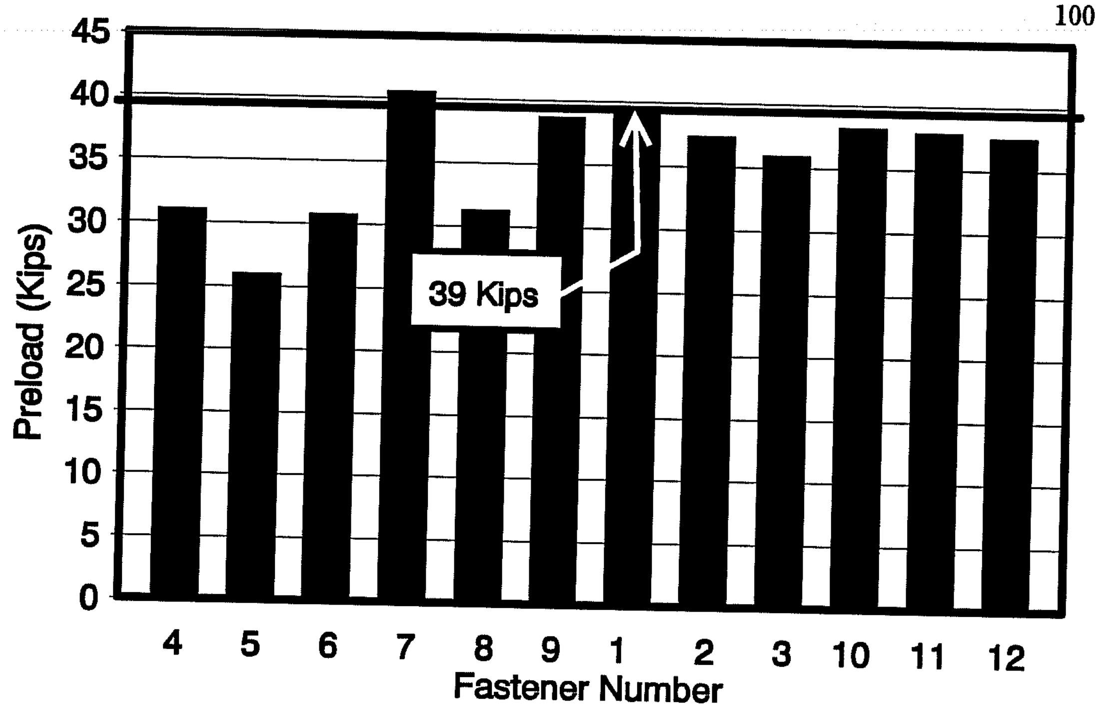


Figure 4.57: Final Installed Tensions for Test CDCW-3

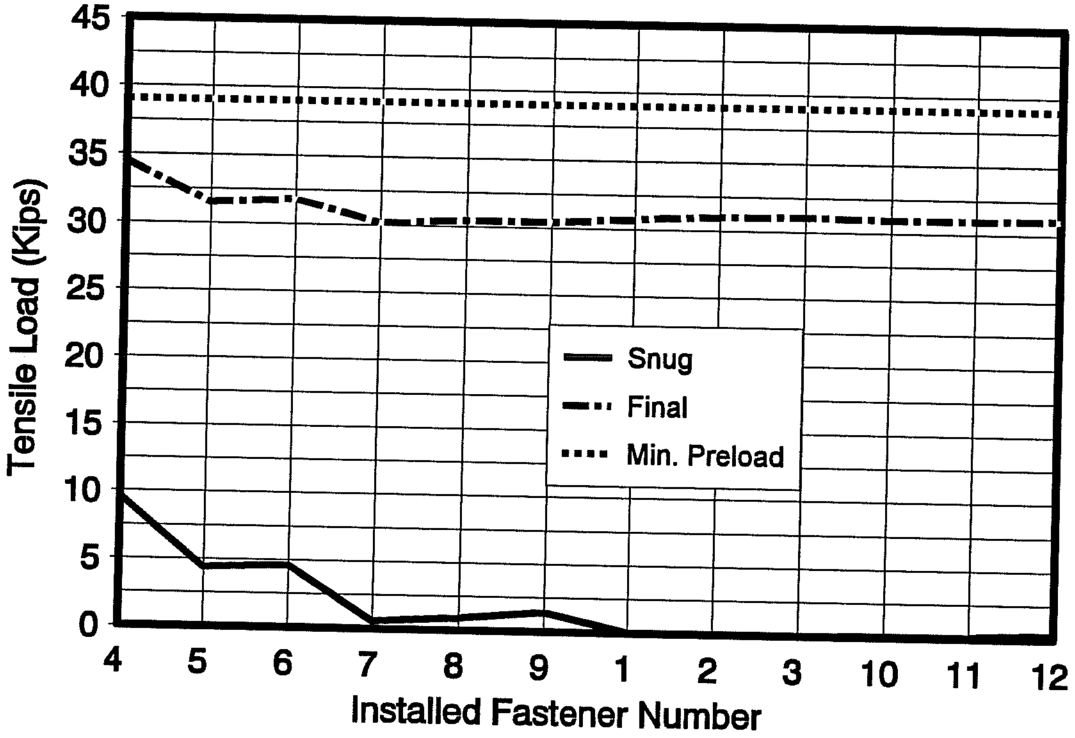


Figure 4.58: Tensile Load History for Fastener #4 - Test CDCW-3

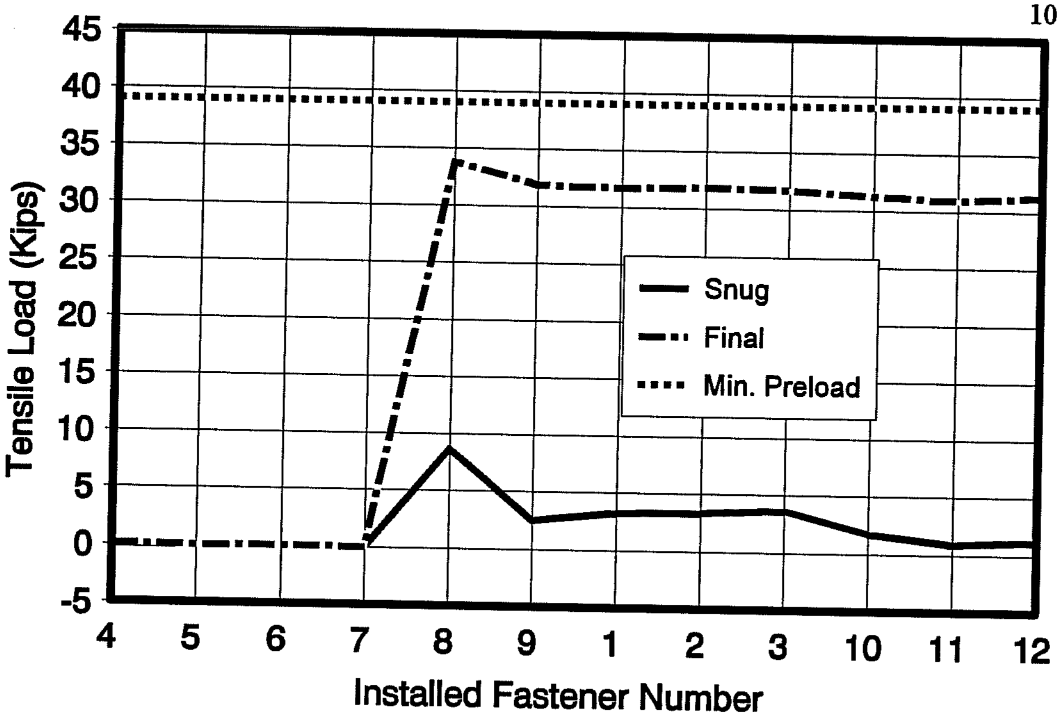


Figure 4.59: Tensile Load History for Fastener #8 - Test CDCW-3

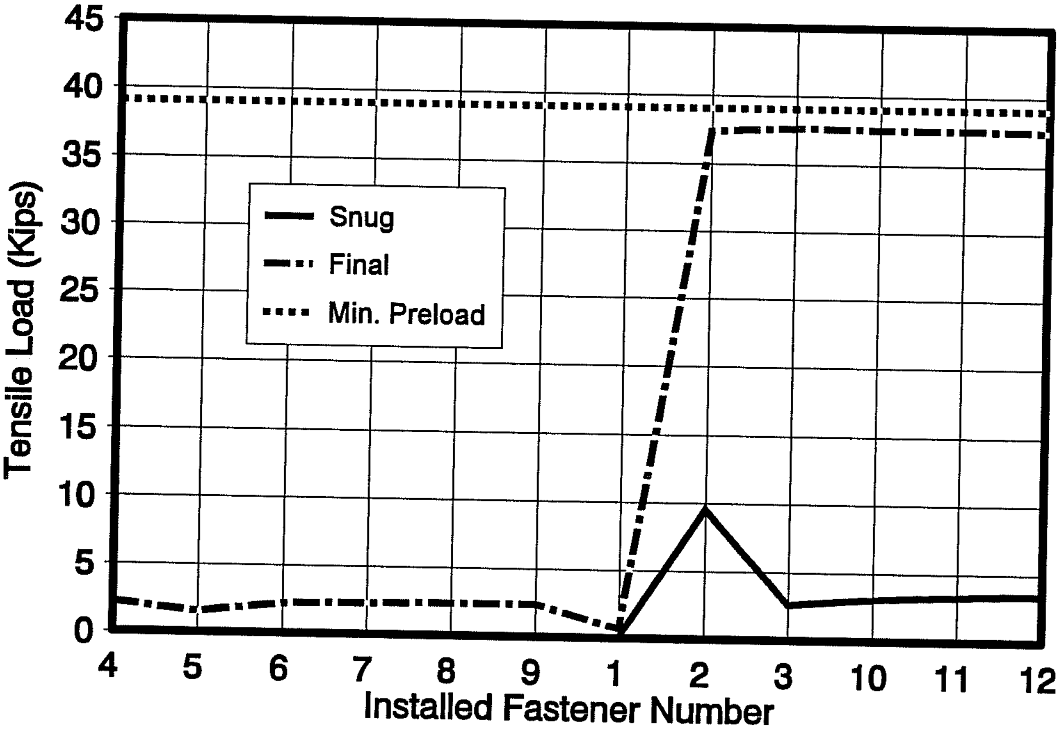


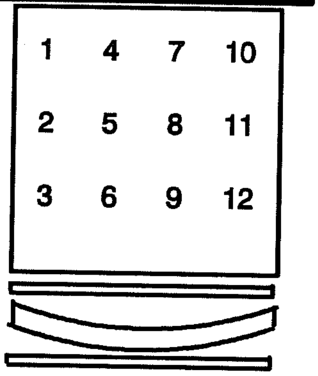
Figure 4.60: Tensile Load History for Fastener #2 - Test CDCW-3

Fastener Number

		4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
Snugging Order	4.0	10.4	0.1	0.1	0.1	0.1	0.1	0	0.1	0	0.8	0.0	0.5
	5.0	4.0	12.0	-0	0	-0	-0	-0	0	-0.1	0.6	-0.1	0.1
	6.0	4.4	5.8	9.0	0	0	0	0.1	0.1	0.1	0.7	0.1	0
	7.0	1.7	3.7	9.6	10.7	-0	-0	-0	0.1	-0	0	-0.1	-0
	8.0	2.9	2.8	8.0	3.8	10.4	0	0	0.1	0.4	0	-0	0.1
	9.0	4.4	3.6	5.0	2.7	3.4	10.9	0.1	0.1	0.1	0.1	0.1	0.3
	1.0	0	0.3	1.2	5.4	5.3	14.2	9.9	0	-0.1	0	0	0.1
	2.0	-0.1	0	0	6.5	5.5	14.7	2.1	10.3	-0	0	-0	0
	3.0	-0.1	-0.1	-0	7.0	6.1	13.7	2.0	1.9	11.5	-0	-0.1	-0.2
	10.0	0.1	0.0	0	1.0	3.2	11.6	4.1	3.5	13.3	9.7	-0	-0.1
	11.0	0.5	0.1	0.1	1.4	1.6	7.5	4.5	3.9	14.7	3.1	12.0	0.1
	12.0	0.7	0.2	0.1	2.1	1.6	2.8	4.5	4.3	15.8	3.3	3.6	12.1
Tightening Order	4.0	36.9	0.0	0	0	0	0	-0	0	12.6	2.5	2.7	12.1
	5.0	21.1	41.2	0.1	0.1	0.1	0.1	0.1	0.1	4.8	3.1	2.2	10.4
	6.0	21.3	28.5	40.1	0	0	0	0	0	-0	3.5	2.7	8.5
	7.0	19.9	29.0	40.4	38.7	0	0	0.2	0	0.3	0.2	0.3	7.7
	8.0	21.6	28.7	39.8	31.3	40.4	0	0.2	0.2	1.2	0.1	-0	2.9
	9.0	22.7	30.4	35.2	30.4	31.4	42.0	0.4	0.3	3.8	0.1	0.1	0.1
	1.0	11.3	22.6	32.5	32.3	32.4	42.3	39.0	0	0	0	0	0.2
	2.0	12.0	20.0	27.4	32.4	32.8	43.6	34.8	44.0	0	0.1	0.0	0.3
	3.0	12.2	20.8	26.5	32.3	32.8	43.8	34.9	41.3	42.1	0	0	0.3
	10.0	13.6	21.5	27.3	18.6	22.8	37.1	34.9	41.3	41.9	39.5	0.0	0.5
	11.0	13.6	21.6	27.8	19.4	19.7	30.5	34.9	41.3	41.8	36.4	42.3	0.5
	12.0	13.6	21.6	27.9	19.6	20.3	28.2	34.9	41.2	41.7	36.5	39.4	39.6
Touch-up Pass	4.0	36.7	21.3	27.8	18.2	20.2	28.3	34.7	41.2	41.6	36.4	39.2	38.7
	5.0	36.3	40.9	27.8	18.2	19.8	28.4	34.8	41.2	41.6	36.4	39.2	38.9
	6.0	36.2	40.3	37.4	18.2	19.7	27.5	34.7	41.2	41.5	36.3	39.2	38.5
	7.0	35.5	40.4	37.2	34.3	19.5	27.7	34.8	41.2	41.6	36.2	39.3	38.8
	8.0	35.3	39.7	37.1	33.8	40.5	27.4	34.8	41.2	41.4	36.2	39.1	38.6
	9.0	35.4	39.7	36.3	33.7	40.3	39.0	34.8	41.1	41.5	36.2	39.2	38.4
	1.0	35.3	39.6	36.3	33.7	40.1	38.9	38.7	41.1	41.4	36.2	39.1	38.4
	2.0	35.3	39.6	36.2	33.6	40.1	38.9	38.5	43.2	41.4	36.2	39.1	38.3
	3.0	35.4	39.7	36.3	33.7	40.1	39.0	38.6	43.1	42.0	36.3	39.0	38.6
	10.0	35.3	39.7	36.3	33.6	40.0	38.9	38.5	43.0	42.0	36.9	39.1	38.7
	11.0	35.2	39.5	36.2	33.6	39.9	38.8	38.4	43.0	41.9	36.8	39.7	38.4
	12.0	35.3	39.6	36.3	33.6	40.0	38.8	38.4	43.0	41.9	36.8	39.7	41.4

Tension in Kips

Average Fastener Tension
(after snugging)= 4.3 Kips
(after tightening)= 30.4 Kips
(after touch-up)= 38.8 Kips
5-1/4" Conventional Fasteners
4" Grip
Deformed Plates
Cal. Wrench Installation (w/Snugging)
(Touch-up Pass)



Fastener Numbers

Figure 4.61: Fastener Tensions for Test CDCW-4

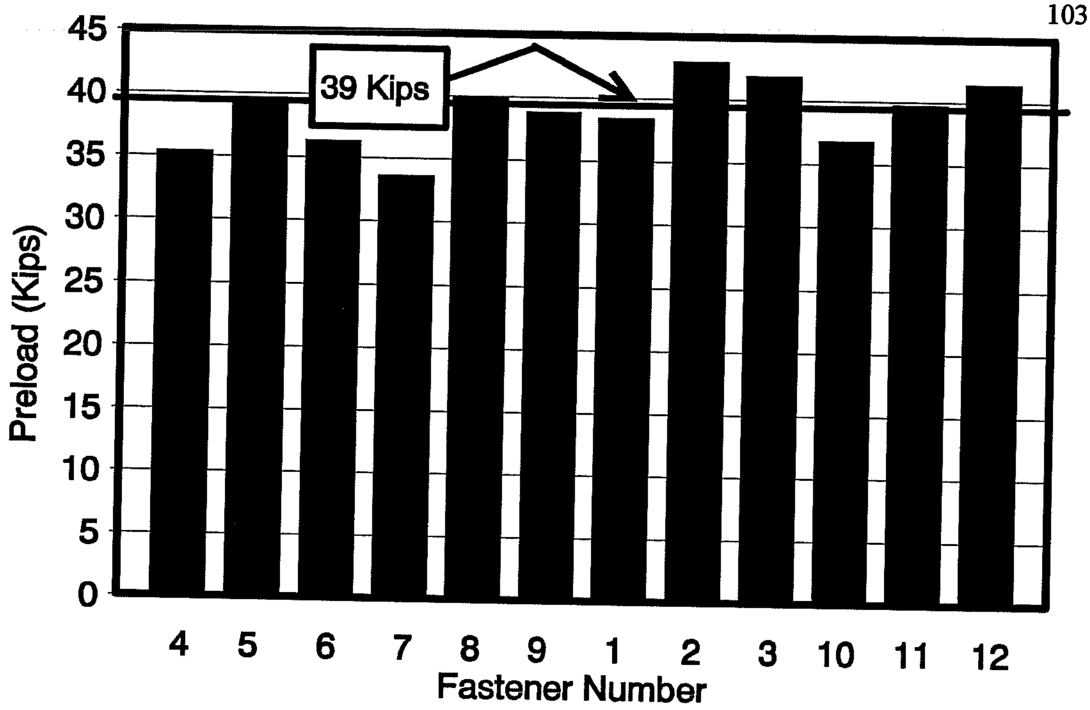


Figure 4.62: Final Installed Tensions for Test CDCW-4

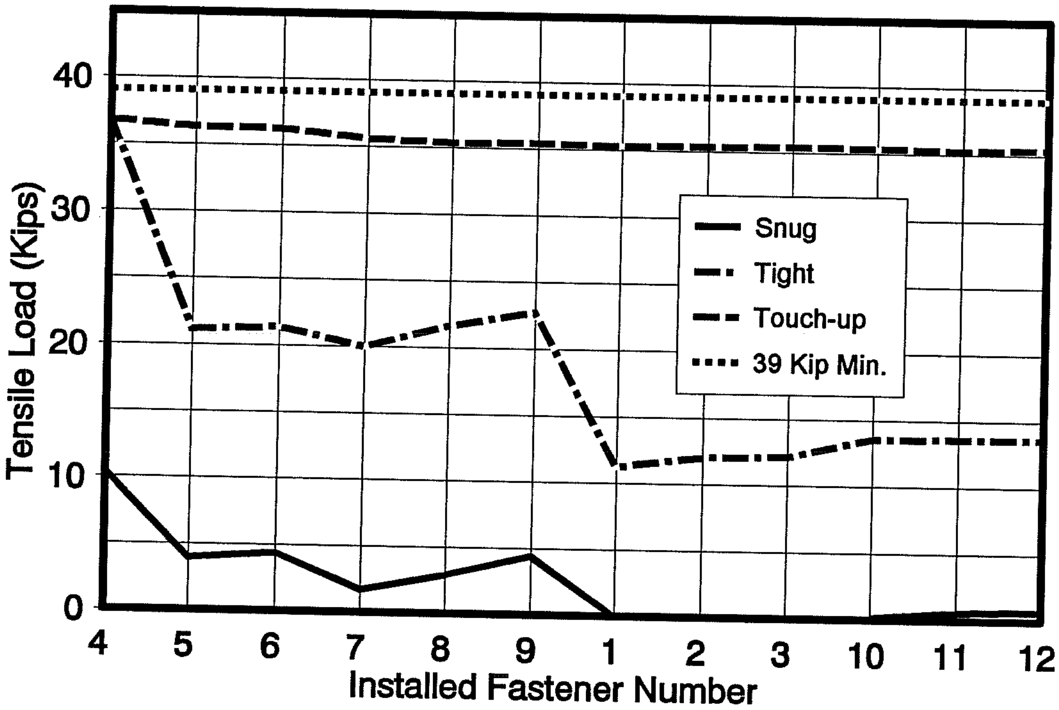


Figure 4.63: Tensile Load History for Fastener #4 - Test CDCW-4

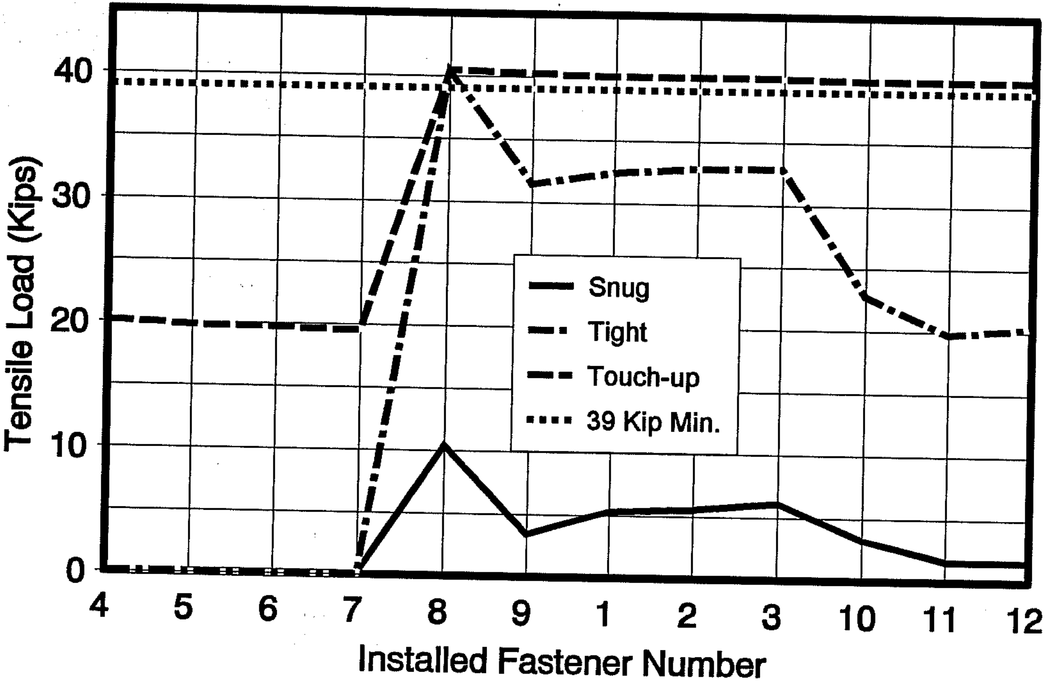


Figure 4.64: Tensile Load History for Fastener #8 - Test CDCW-4

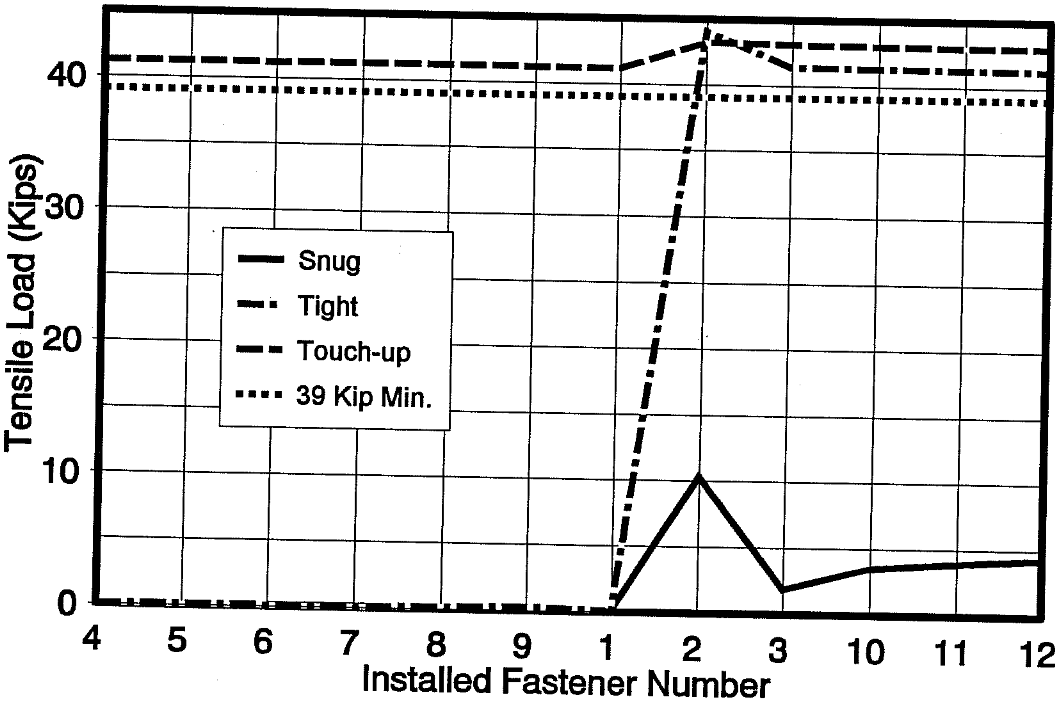


Figure 4.65: Tensile Load History for Fastener #2 - Test CDCW-4

Figures 4.66 through 4.68 show photographs of the test connection in the original (pre-test) condition, after the snugging pass, and after the final tightening pass (after touch-up). Note that the snug loads were unable to pull out all of the visible gap in the plates. Upon final tightening, however, all visible gap appeared to have been removed from the connection plates.

4.3.3 TURN-OF-NUT INSTALLATION METHOD

These tests were conducted using the same turn-of-nut procedure detailed in Section 4.2.2. The deformed plate, turn-of-nut installation method tests are designated as the CDTON series.

4.3.3.1 TEST RESULTS

As in the turn-of-nut tests described in Section 4.2.2, the fasteners used for the following tests also exhibited yielding in the unthreaded portion of their shanks. Final tensile load measurement was accomplished as described in Section 3.4.6. Accordingly, for these CDTON tests, only the fastener tensions measured during snugging and at the fully tightened condition are reported.

Table 4.8 is a summary of the important fastener tensile load results that were observed during these tests. The table lists the average values of final fastener tension, initial snug fastener tension, and fastener tension loss during the snugging sequence. The final tensions are those measured in the bolts subsequent to the tightening of the last bolt in the connection by measured nut rotation past snug tight. Initial snug fastener tension refers to the tension developed in that fastener immediately after snugging of that fastener during the snugging pass. Snug tension loss is the difference between the initial snug load of a fastener and the load in the same fastener upon completion of the snugging pass for all connection fasteners. Standard deviations for all quantities are also listed.

Test CDTON-2:

Figures 4.69 through 4.73 and Table 4.8 present the results of this test. Upon final tightening to 1/3 of a turn past snug tight, the average tensile load in each bolt was 51.5 kips, well above the 39 kip minimum. The loss of snug tension in both the interior and exterior rows of the connection was minimum with average losses of 0.6 and 0.1 kips, respectively (see Table 4.8). Figures 4.71 through 4.73 illustrate the relatively constant snug loads in bolts 4, 8, and 2. During the snugging process, some fasteners exhibited an increase in load due to the tightening of others. Snugging with the spud wrench produced widely varying values of initial snug tension in the bolts

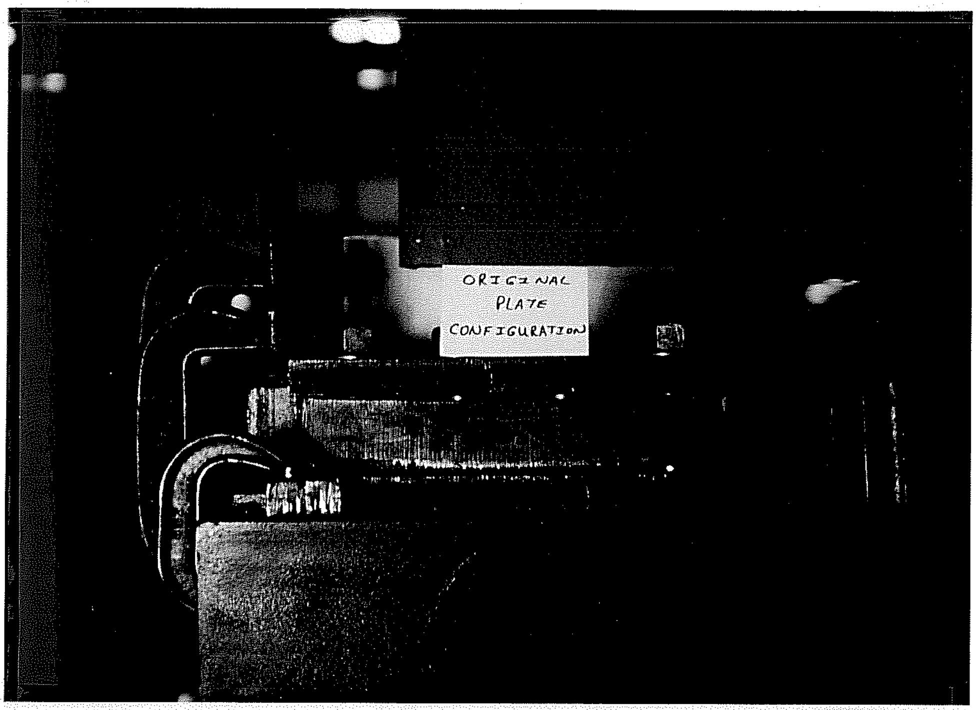


Figure 4.66: Connection plates for test CDCW-4 in pre-test condition

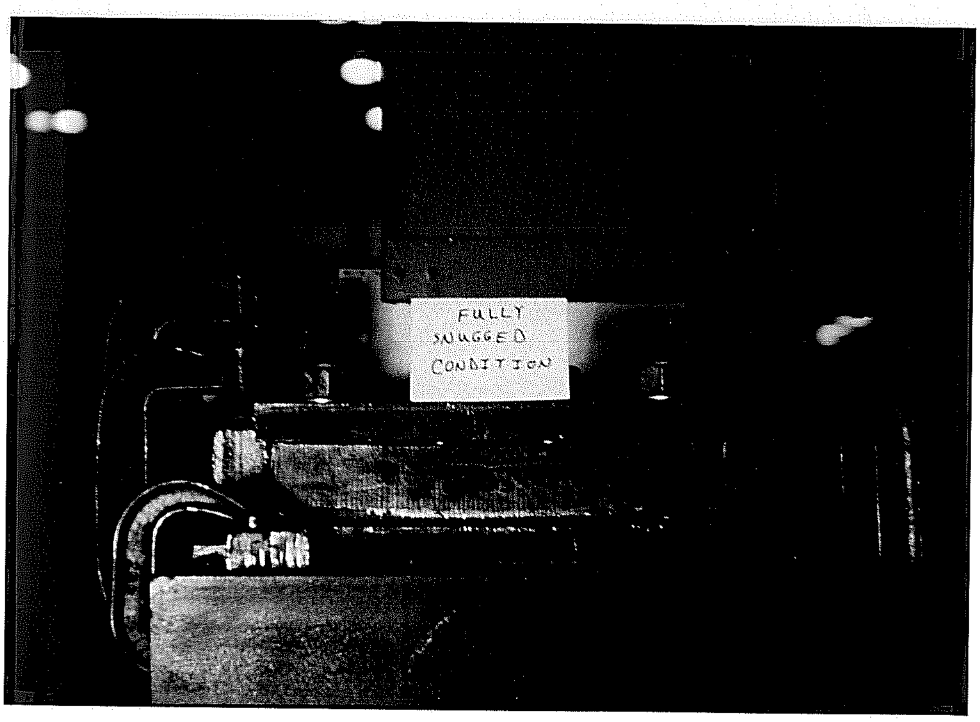


Figure 4.67: Connection plates for test CDCW-4 in fully snugged condition

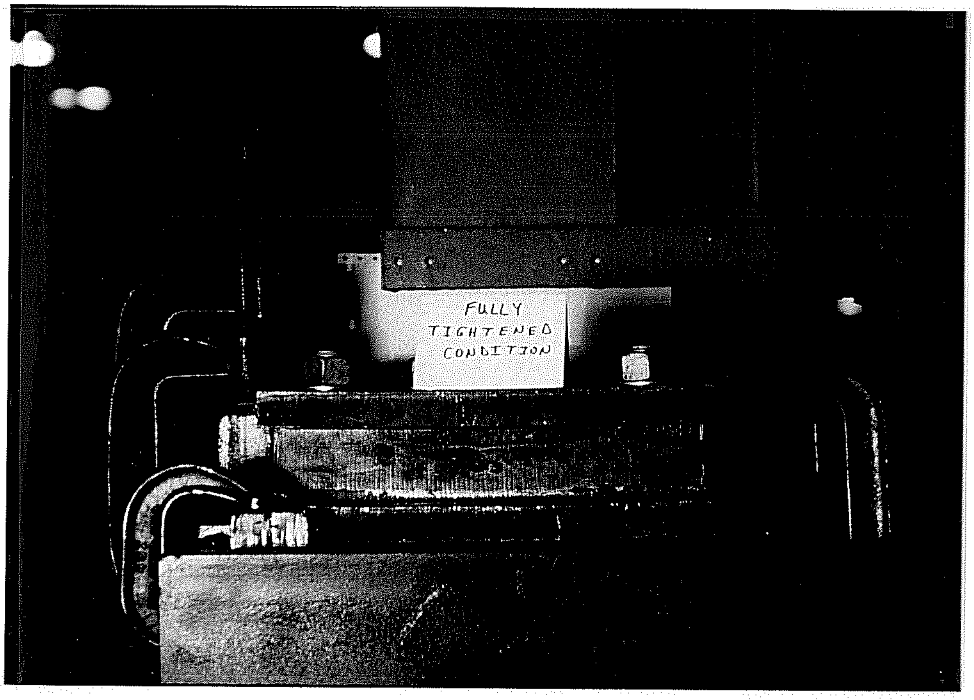


Figure 4.68: Connection plates for test CDCW-4 in fully tightened condition

Test #	Average Final Fastener Tension	Standard Deviation	Average Initial Snug Fastener Tension	Standard Deviation	Average Snug Tension Loss in Interior Rows	Standard Deviation	Average Snug Tension Loss in Exterior Rows	Standard Deviation
CDTON-2	51.5	2.8	35.0	4.8	0.6	1.2	0.1	0.4
CDTON-3	50.9	4.7	30.0	3.6	6.7	3.4	0.6	0.4
CDTON-4	49.7	4.5	32.3	5.2	12.4	3.1	2.4	1.5

Note: All values in Kips

Table 4.8: Summary of fastener load results for CDTON series tests

as evidenced by the standard deviation of 4.8 kips from the mean initial tension value. The maximum observed variation between initial individual fastener snug loads was 16.2 kips.

Test CDTON-3:

The results of this 3" grip test can be seen in Figures 4.74 to 4.78 and in Table 4.8. The average final installed fastener tension for the test was 50.9 kips, which agrees with the corresponding high values indicated by the other turn-of-nut tests. Fairly high losses of tensile load were observed during snugging in the interior bolts (6.7 kips on average) while the exterior fasteners lost very little preload. To illustrate this, compare Figures 4.76 and 4.77 (interior bolts 4 and 8) to Figure 4.78 (exterior bolt 2). As was observed in test CDTON-2, snugging by the use of the spud wrench produced very inconsistent initial snug tensile loads in the fasteners (std. deviation= 3.6 kips). The maximum variation in the initial individual fastener snug loads was 12.6 kips.

Test CDTON-4:

Figures 4.79 to 4.83 and Table 4.8 present the results of this test. The final average installed fastener tension was 49.7 kips as indicated in Figure 4.79. As in the 3" grip test, the interior fasteners (#4-9) lost a good portion of their initial snug loads in the course of the snugging pass. The average loss was 12.4 kips per Table 4.8. The exterior fasteners also experienced tension losses (2.4 kips on average), although not of the magnitudes exhibited by the interior bolts. Figures 4.81 and 4.82 show graphically the relatively large losses of snug load in bolts 4 and 8 (interior) while Figure 4.83 illustrates the lesser relaxation of bolt 2 (exterior). The initial snug loads induced in the fasteners by the use of the spud wrench were highly varied, with a standard deviation from the mean of just over 5 kips.

4.4 CONCLUSIONS OF THE CONVENTIONAL A325 FASTENER TESTS

Table 4.9 is a summary of all the connection tests conducted with conventional A325 fasteners. Test conditions as well as final average tensions are summarized. The average final installed tensions listed are based on the measured fastener loads after the last installation pass, either tightening or touch-up. From the results of these tests the following conclusions may be derived:

1.) The calibrated wrench (Section 4.2.1) method of installation, conducted without snugging, produced adequate average fastener preload in the flat plate connection tests. For

Fastener Number

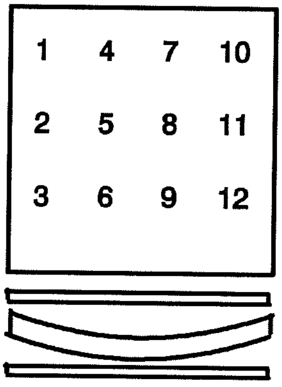
Snugging Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	28.8	-0.2	-0.1	-0	-0.1	-0.2	-0.1	0.0	-0.2	-0.1	-0	-0
5.0	28.2	33.7	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.6	0.1
6.0	28.1	33.2	35.9	0.1	0	-0	0	0.1	0	0	0.2	0.1
7.0	28.5	33.5	35.7	29.6	-0.1	0	0	0.1	-0	0.1	0	0
8.0	28.6	33.8	35.6	27.5	31.8	0.0	-0.1	-0	-0.1	0.0	-0	-0.1
9.0	28.6	33.7	35.3	27.4	30.4	38.4	-0.1	-0	-0.1	-0.1	-0.2	-0
1.0	29.2	33.9	35.4	27.4	30.5	38.3	34.1	0.1	0.1	0.1	0	0.1
2.0	29.2	34.3	35.5	27.4	30.5	38.3	33.9	39.9	0.1	0.1	0	0
3.0	29.2	34.2	35.7	27.4	30.3	38.0	33.7	39.5	38.8	-0	-0	0.1
10.0	29.3	34.2	35.8	26.7	30.2	37.9	33.8	39.4	38.8	27.1	0.4	0.1
11.0	29.2	34.4	36.0	26.8	30.4	38.1	33.8	39.4	38.8	27.8	38.0	0.1
12.0	29.2	34.3	35.9	26.7	30.4	38.4	33.7	39.3	38.7	27.6	38.2	43.3
Final	51.3	48.6	50.2	49.4	50.0	53.4	54.4	57.5	48.0	50.5	54.9	49.6

Tension in Kips

Average Fastener Tension = 51.5 Kips

3-1/4" Conventional Fasteners
2" Grip
Deformed Plates
Turn-of-Nut Installation



Fastener Numbers

Figure 4.69: Fastener Tensions for Test CDTON-2

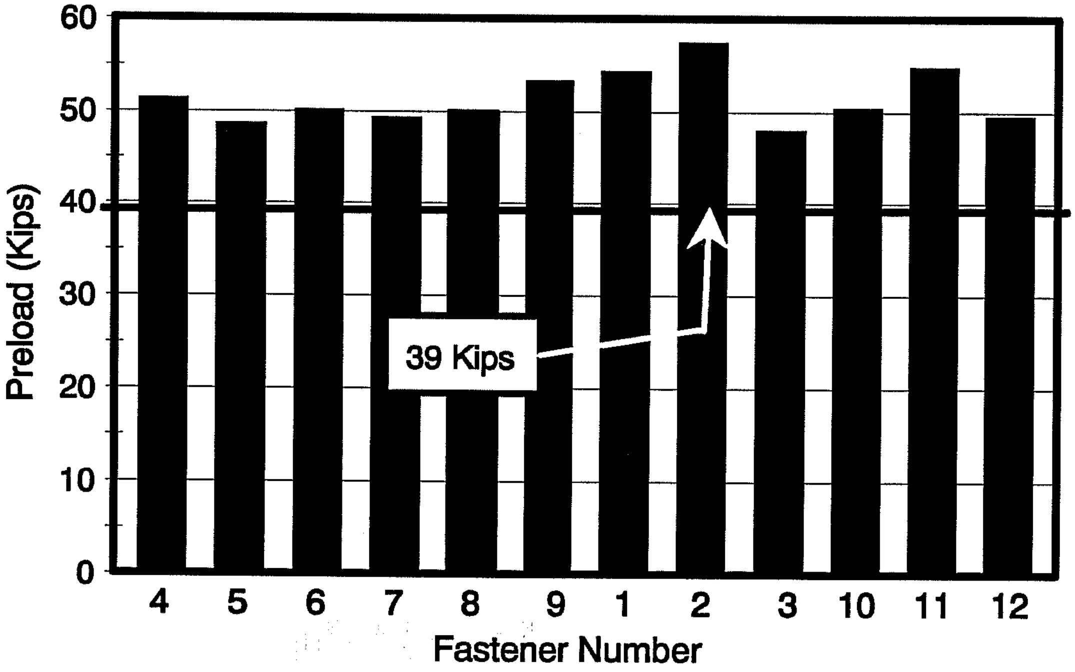


Figure 4.70: Final Installed Tensions for Test CDTON-2

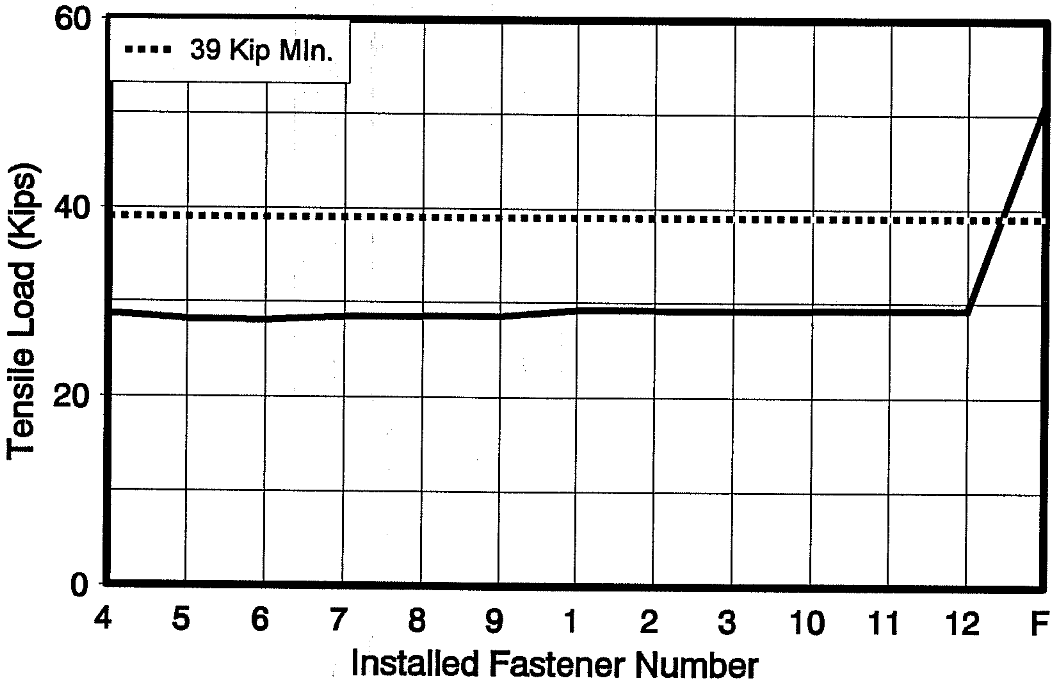


Figure 4.71: Tensile Load History for Fastener #4 - Test CDTON-2

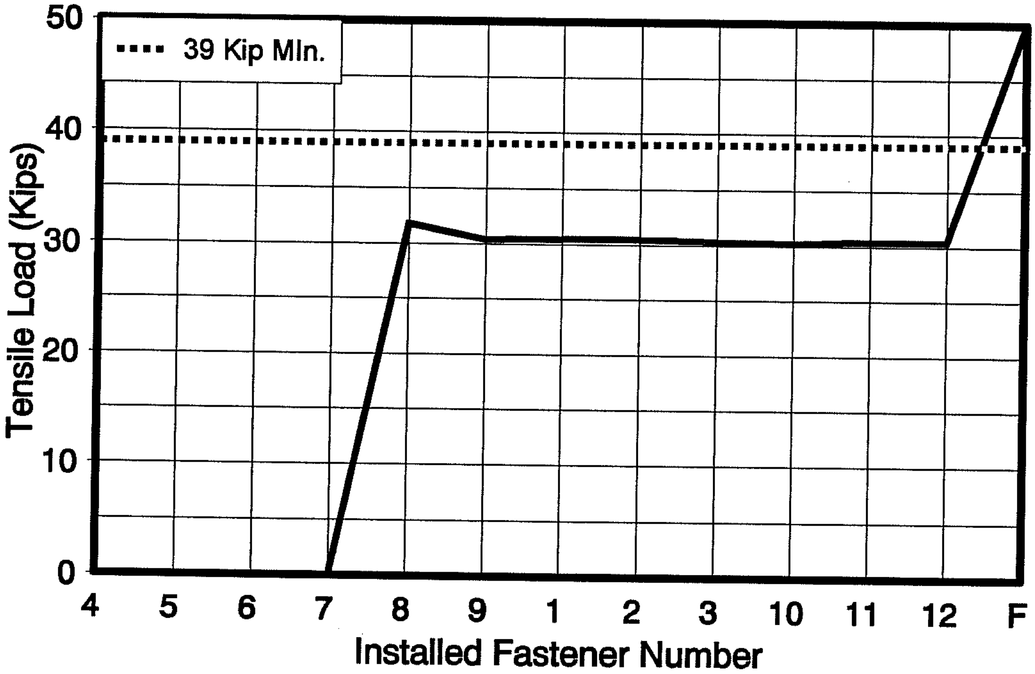


Figure 4.72: Tensile Load History for Fastener #8 - Test CDTON-2

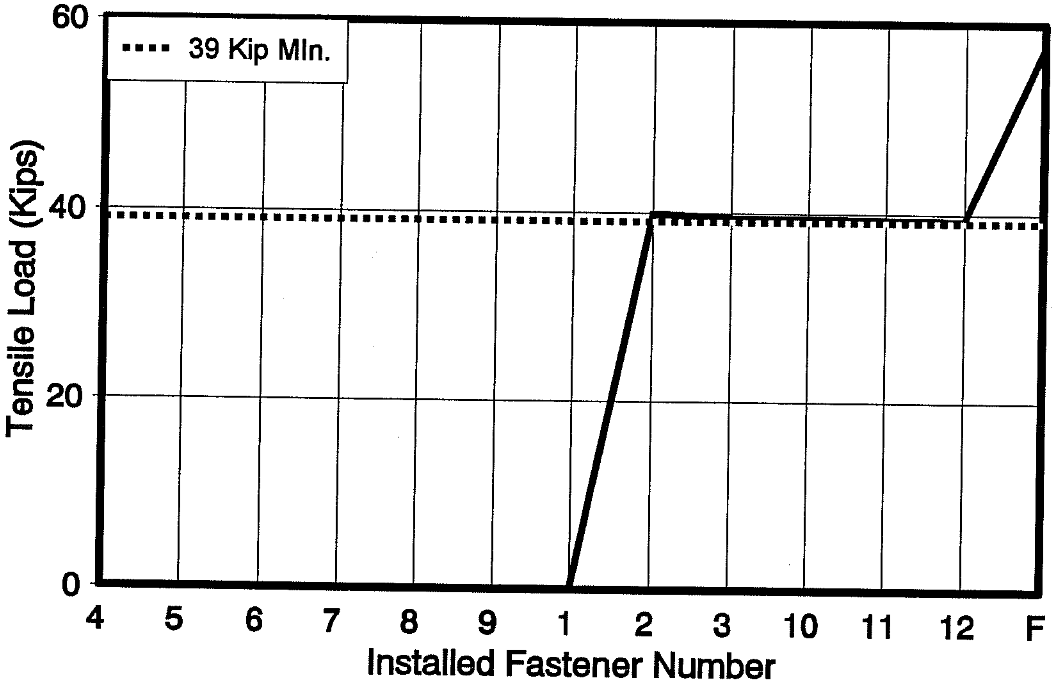


Figure 4.73: Tensile Load History for Fastener #2 - Test CDTON-2

Fastener Number

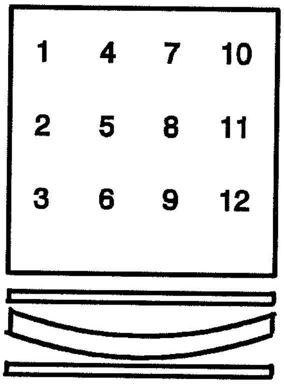
Snugging Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	22.2	0	0	0.2	0	0.1	0.1	-0.1	0.2	1.3	0.1	0
5.0	13.9	29.4	0	0	0	0.2	0	-0	0	1.4	0	0
6.0	14.5	22.8	31.8	0.2	0.1	0.2	0.1	-0	0.2	1.7	0.2	0.1
7.0	16.1	23.2	31.4	25.3	0	0.2	0	0	0	-0	0	0
8.0	17.6	23.8	31.6	19.1	27.0	0.3	0	0.0	0.1	0	0.1	0
9.0	18.0	26.0	31.4	18.5	20.5	34.8	0.1	-0.1	0.1	0.0	0.1	0.1
1.0	14.3	23.3	29.5	19.2	20.8	34.6	33.4	-0.1	0.2	0.1	0.2	0.1
2.0	14.7	22.8	27.0	19.1	20.9	34.5	32.4	30.7	0	-0	0	0.0
3.0	14.8	23.5	25.5	19.1	21.1	34.5	32.6	29.4	30.5	0.0	0.1	0.1
10.0	15.3	23.6	25.7	14.0	17.7	34.3	32.5	29.3	30.2	28.5	0.1	0
11.0	15.3	23.7	25.8	14.4	17.0	34.4	32.5	29.3	30.1	28.2	32.6	0
12.0	15.1	23.7	25.9	14.3	17.3	34.3	32.5	29.4	30.0	28.2	32.4	34.3
Final	41.3	49.6	54.9	54.9	50.0	54.7	57.0	46.5	52.8	54.2	50.3	44.0

Tension in Kips

Average Fastener Tension = 50.9 Kips

4-1/4" Conventional Fasteners
3" Grip
Deformed Plates
Turn-of-Nut Installation



Fastener Numbers

Figure 4.74: Fastener Tensions for Test CDTON-3

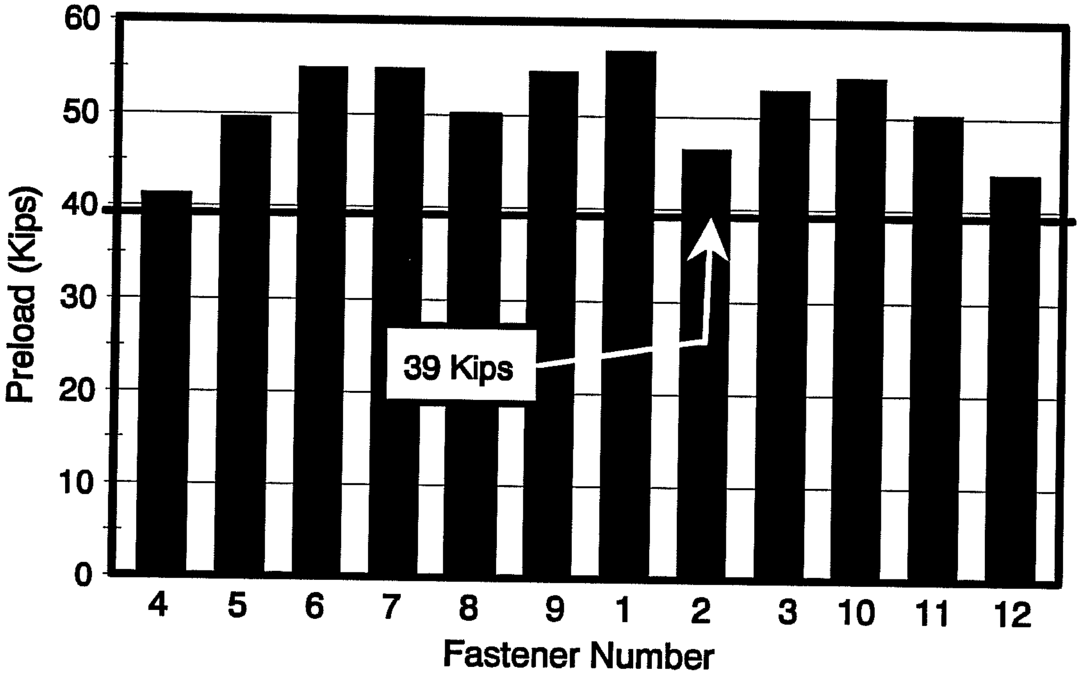


Figure 4.75: Final Installed Tensions for Test CDTON-3

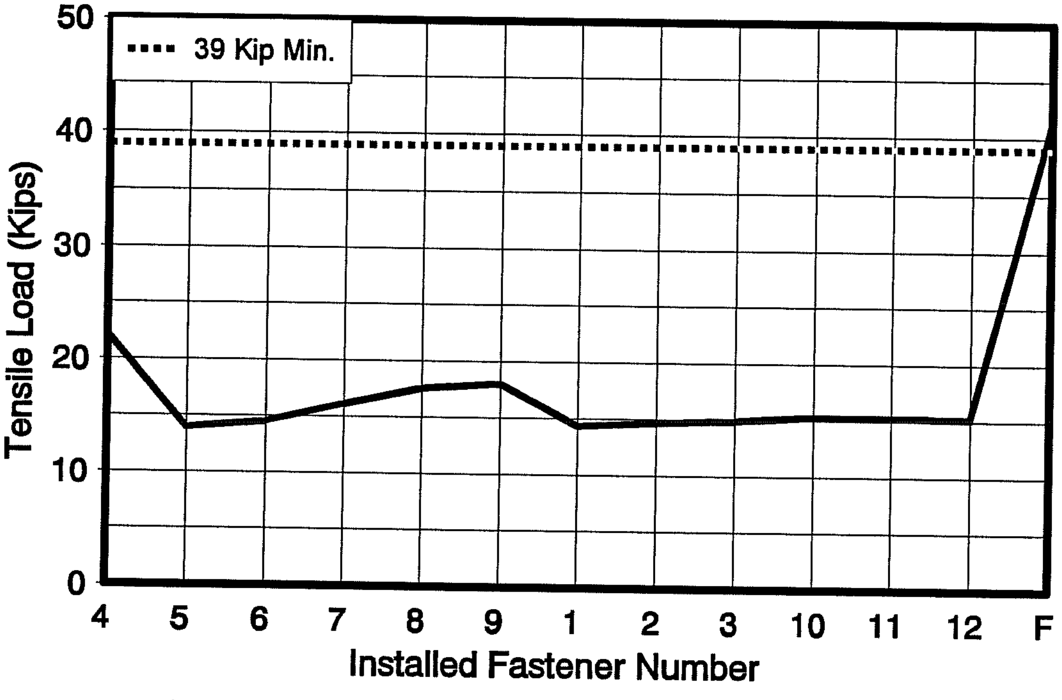


Figure 4.76: Tensile Load History for Fastener #4 - Test CDTON-3

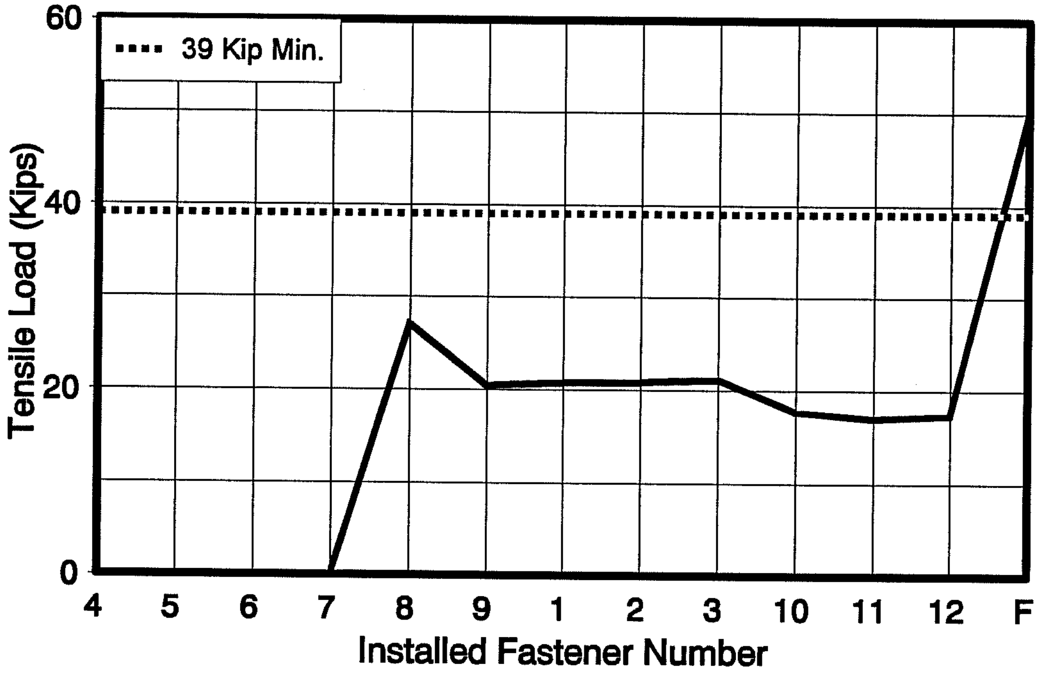


Figure 4.77: Tensile Load History for Fastener #8 - Test CDTON-3

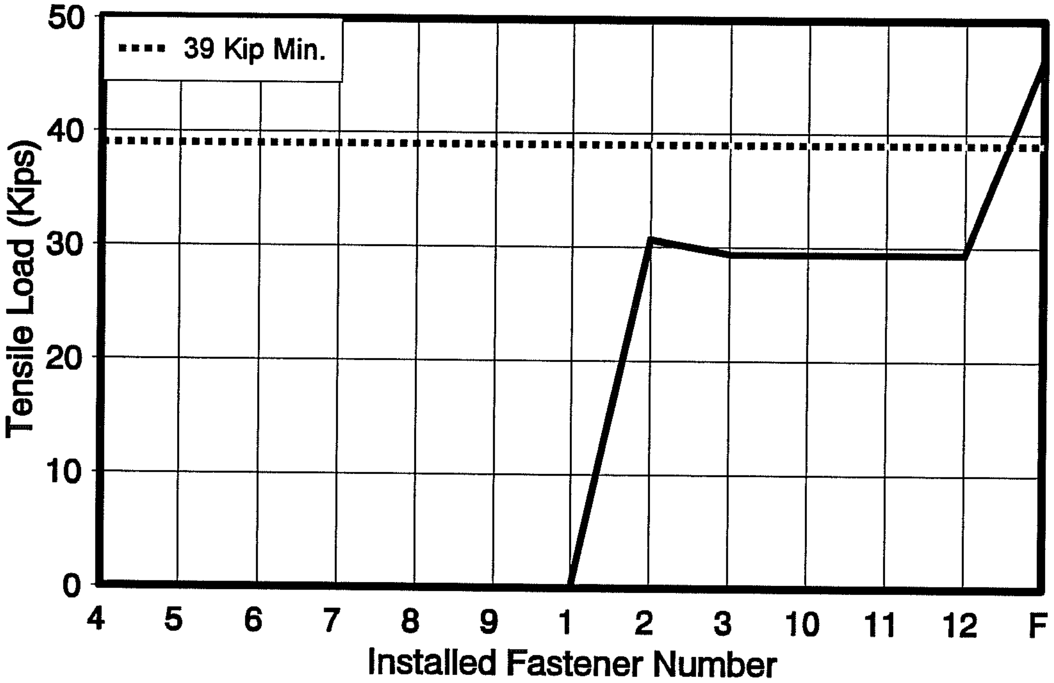


Figure 4.78: Tensile Load History for Fastener #2 - Test CDTON-3

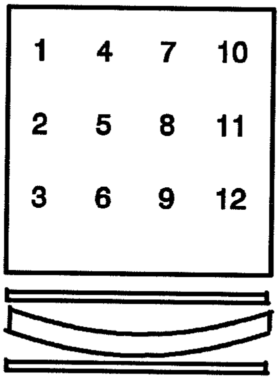
Fastener Number

Snugging Order	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	25.6	-0.2	-0.3	-0.2	-0.1	-0.2	-0.2	-0.2	-0.1	-0	-0.1	2.2
5.0	13.7	26.1	-0.2	-0.2	-0.1	-0.3	-0.2	-0.1	-0.2	0.3	-0.2	1.8
6.0	13.9	15.4	32.8	0.2	0.2	-0.1	0.1	0.3	-1.0	0.9	0.1	1.5
7.0	12.8	14.8	32.4	24.5	0.2	-0	0.1	0.2	0.2	0.1	0.2	0.5
8.0	16.5	16.6	33.8	14.8	34.8	0	0.2	0.3	0.2	0.2	0.2	-0.1
9.0	18.6	20.2	31.7	13.6	25.1	38.4	0.2	0.3	0.5	0.1	0.5	-0.2
1.0	9.4	13.4	27.8	17.2	27.2	39.6	28.6	0.2	0.2	0.2	0.2	-0.4
2.0	10.0	10.8	23.3	17.7	28.2	41.1	24.0	33.5	0.2	0.1	0.2	-0.4
3.0	10.1	11.5	22.3	17.6	28.4	41.8	24.2	30.4	38.5	0	0.2	-0.4
10.0	12.0	12.3	23.0	8.3	21.1	37.3	24.1	30.5	38.1	29.0	0.2	-0.2
11.0	12.1	12.6	23.5	8.9	18.8	32.6	24.2	30.5	38.0	26.9	37.6	-0.3
12.0	12.1	12.7	23.6	9.0	19.2	31.1	24.1	30.4	38.7	26.9	35.3	38.7
Final	43.9	50.9	43.8	48.0	52.1	52.6	56.6	53.3	44.8	53.5	43.0	53.7

Tension in Kips

Average Fastener Tension = 49.7 Kips

5-1/4" Conventional Fasteners
4" Grip
Deformed Plates
Turn-of-Nut Installation



1	4	7	10
2	5	8	11
3	6	9	12

Fastener Numbers

Figure 4.79: Fastener Tensions for Test CDTON-4

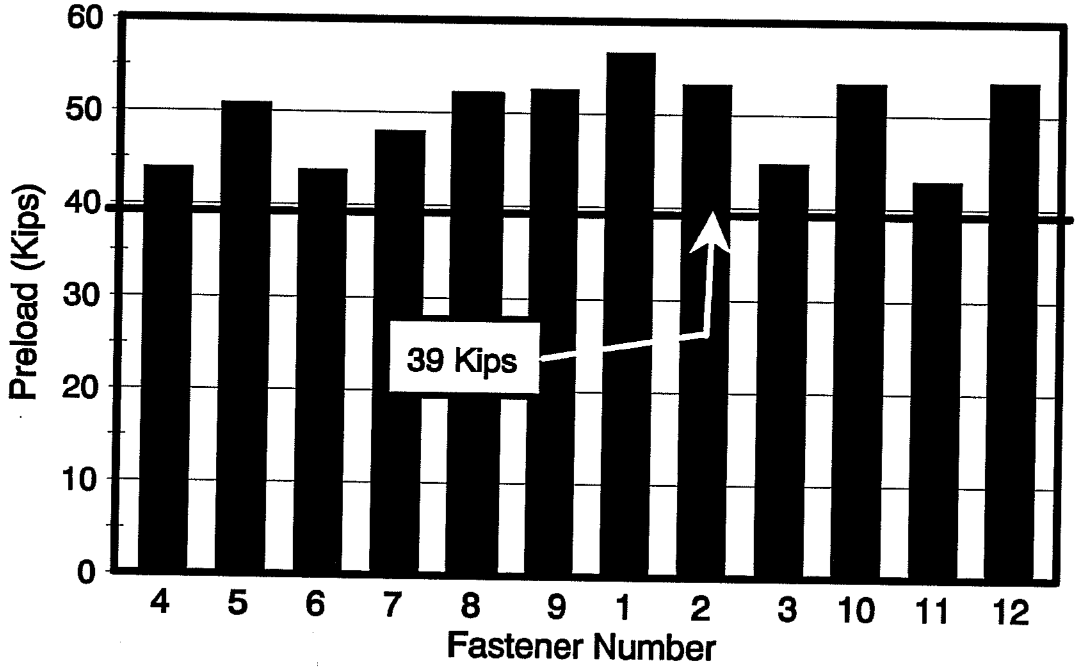


Figure 4.80: Final Installed Tensions for Test CDTON-4

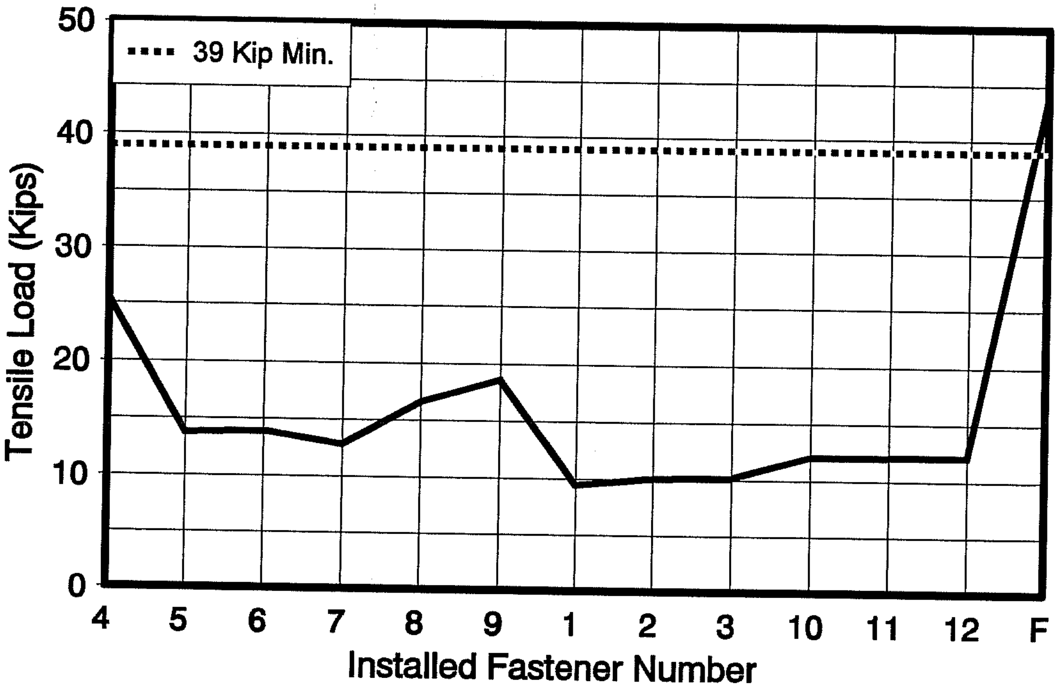


Figure 4.81: Tensile Load History for Fastener #4 - Test CDTON-4

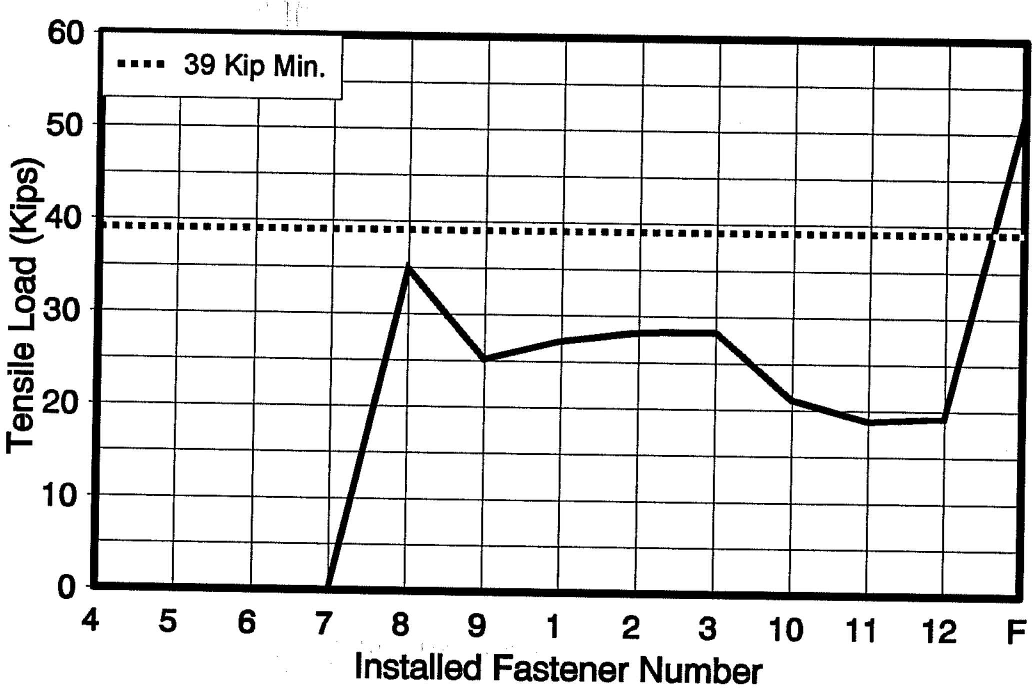


Figure 4.82: Tensile Load History for Fastener #8 - Test CDTON-4

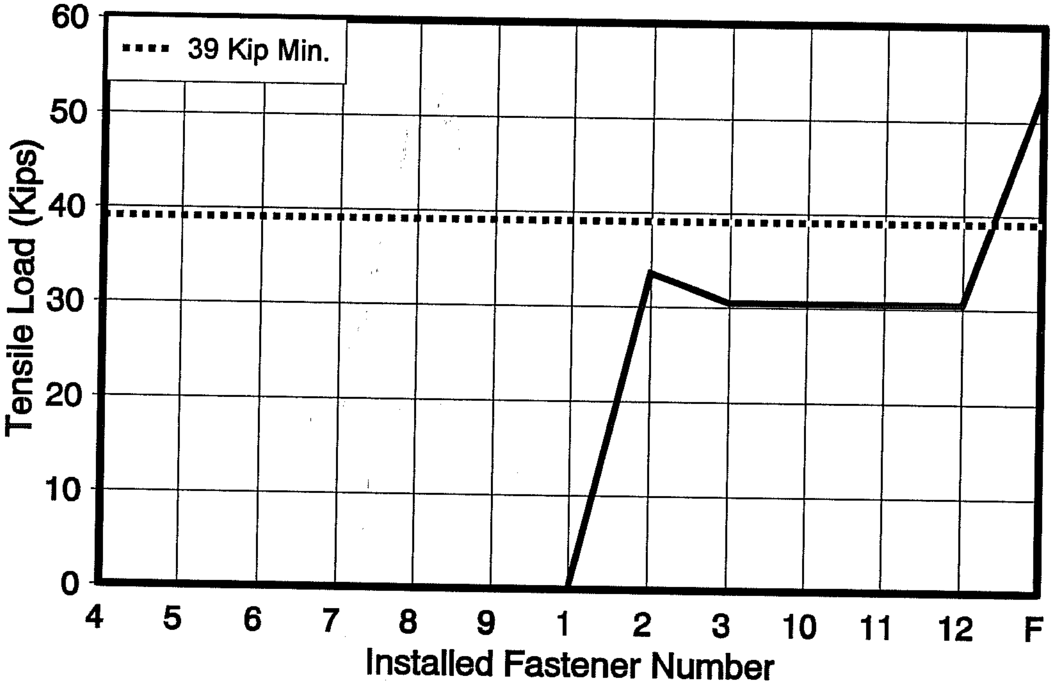


Figure 4.83: Tensile Load History for Fastener #2 - Test CDTON-4

nominally flat plates, the lack of snugging did not adversely affect the final installed tensions in the connection fasteners, as demonstrated in Table 4.1.

2.) The presence of a deformed middle plate in the tested connections produced losses in the initially induced tensions of the fasteners with which the connections were joined. As compared to bolts in joints with nominally flat middle plates, the installed fasteners in the deformed plate joints exhibited much higher tensile load losses during the fastener installation sequence.

The observed preload loss is apparently due to the inability of the initially installed bolts to compress the gap in the plies of the connection. As succeeding bolts are installed, more of the remaining gap is reduced and the preload of previously tensioned fasteners drops. Thicker plates, with their greater bending stiffness, require large fastener tensile forces to compress the plate gap. Accordingly, less gap is reduced due to individual fastener installation and more is left to be compressed by the tensions developed in subsequent fasteners.

Consistent with this reasoning is the fact that the observed tensile load losses were of much higher magnitudes in fasteners located in the interior of the connection than in those installed in the exterior rows. The interior fasteners had more gap to compress and were, thus, susceptible to greater tensile load relaxation during the installation sequence. Loss of preload increased with increasing grip thickness, as would be expected. The degree of preload loss during an installation pass was also dependent upon the magnitude of the load in the fasteners (and, thus, the remaining plate gap) prior to the start of the installation pass. For example, fasteners tensioned directly to 39 kips from an initially unloaded state (CDCWNS series tests) exhibited much higher tensile load losses than those being touched-up during calibrated wrench installation (see test CDCW-4).

3.) The turn-of-nut method applied as described in Section 4.2.2 produced average preloads in the fasteners of both flat and deformed plate connections that well exceeded the 39 kip minimum value (see Tables 4.2 and 4.8). Snugging for the turn-of-nut tests was accomplished with an ordinary spud wrench and was conducted under ideal conditions (unrestricted access to the connection, adequate leverage on the wrench, etc...). The snug loads produced during turn-of-nut installation were significantly higher than those observed in the calibrated wrench tests.

Test	Grip	Plate Conditions	Installation Method	Aver. Tension
CFCWNS-2	2"	Flat	Cal. Wrench (w/o snugging)	39.3
CFCWNS-3	3"	Flat	Cal. Wrench (w/o snugging)	40.9
CFCWNS-4	4"	Flat	Cal. Wrench (w/o snugging)	42.0
CFTON-2	2"	Flat	Turn-of-Nut	54.5
CFTON-3	3"	Flat	Turn-of-Nut	51.7
CFTON-4	4"	Flat	Turn-of-Nut	55.0
CDCWNS-2	2"	Middle Plate Δ=3mm	Cal. Wrench (w/o snugging)	39.8
CDCWNS-3	3"	Middle Plate Δ=3mm	Cal. Wrench (w/o snugging) Touch-up Pass	36.1
CDCWNS-4	4"	Middle Plate Δ=3mm	Cal. Wrench (w/o snugging) Touch-up Pass	38.0
CDCW-2	2"	Middle Plate Δ=3mm	Cal. Wrench Two Pass (snug. + tight.)	39.5
CDCW-3	3"	Middle Plate Δ=3mm	Cal. Wrench Two Pass (snug. + tight.)	35.4
CDCW-4	4"	Middle Plate Δ=3mm	Cal. Wrench Three Pass (snug. + tight. + touch-up)	38.8
CDTON-2	2"	Middle Plate Δ=3mm	Turn-of-Nut	51.5
CDTON-3	3"	Middle Plate Δ=3mm	Turn-of-Nut	50.9
CDTON-4	4"	Middle Plate Δ=3mm	Turn-of-Nut	49.7

Table 4.9: Summary of Conventional A325 fastener connection tests

4.) For both the deformed and flat plate conditions, the initial tensions induced in the fasteners by the calibrated wrench installation method were highly variable. This condition occurred during snugging, tightening, and touch-up of the fasteners as is indicated in Table 4.1 and Tables 4.3 through 4.7. These results support the assertion that the torque-load relationship for threaded fasteners is quite variable [2]. Some of the measured tensile loads developed in the fasteners were below the 41 kip target load (39 kips + 5%) for calibrated wrench installation. This occurred despite testing of fasteners in the Skidmore prior to installation to ensure the ability of the set torque to produce 41 kips of fastener tension. A possible solution to these low fastener tensions induced by the calibrated wrench would be to increase the target load of the procedure to greater than 5% above the minimum required tension.

5.) In the deformed plate tests on the 3" and 4" grip connections, the snugging of fasteners to 12 kips was not adequate to prevent large preload losses in the subsequent single tightening pass with the torque wrench during calibrated wrench installation.

CHAPTER 5

CONNECTION TESTS WITH HUCK C50L FASTENERS

5.1 GENERAL

This chapter describes nine connection tests conducted using Huck International C50L lock-pin and collar fasteners. The Huck fasteners were installed in both flat and deformed plates as described in Section 4.1. The connection geometry was identical to the set-up used in the conventional A325 tests of Chapter 4. See Figure 4.1 for an illustration of this layout. The plates utilized in the conventional A325 tests were reused for the Huck fastener tests. All plate deformations were checked as described in Section 4.3 and the plates were rebent as necessary prior to, and during, the testing program. The bars which were used to prevent bolt head rotation in the previous tests (Figure 4.3) were not needed in these Huck fastener tests and were omitted from the test set-up. As before, the plates were not secured to the test fixture, nor were they prevented from deforming in any way during installation.

All fasteners used in the tests were mechanically galvanized 7/8" diameter Huck C50L fasteners (part #C50LFR-DBR28). Fastener length designations were 28, 44, and 60 grip for the 2", 3", and 4" grip tests, respectively.

All lock-pins were paired with a non-galvanized LC collar. Upon receipt of the pins and collars from Huck International, selected tests were performed on a sample of each to verify their compliance with ASTM A325 specifications and their ability to develop adequate clamping loads (fastener tensions) during installation. The details and results of these procedures are detailed in Appendix A at the back of this report. All fasteners were manufactured at the Huck International Inc., facility in Waco, Texas.

Note that these fastener grip lengths used for these tests are different than those of the fasteners used in the evaluation/reliability tests described in Chapter 3. The difference is due to the fact that 3LC collars were used with the lock-pins in the evaluation/reliability tests while LC collars were used in the hereafter described tests. The 3LC collar is a longer collar and requires a longer lock-pin to achieve full collar swage during installation. The change to the LC collar was requested by Huck International.

The Huck fastener tests sought to investigate the effects of several variables on fastener tension at both the snug tight and fully tightened conditions. These variables are summarized as follows:

Length of grip: 2", 3", or 4" total splice thickness

Method of installation: Single pass installation with no snugging
Two pass installation with initial snugging pass
Deformation of plates: Nominally flat or middle plate in singular curvature bending with mid-span deflection of 3mm

The condition of each variable was altered from test to test so that each connection tested was a unique combination of the three individual variables.

To conveniently record and index the results of the Huck fastener tests a special system is used to name each individual test. Each test is described according to the type of fastener used, the flatness condition of the test plates, the method of fastener installation, and the thickness of the test grip. The syntax of the system is as follows:

1st Letter: Type of fastener
    H: Huck C50L fasteners (uniform for this chapter)
2nd Letter: Plate flatness condition
    F: Flat plates
    D: Deformed interior plate
Succeeding Letters: Method of fastener installation
    NS: Single pass with no snugging
    S: Two pass with initial snugging pass
Numerical suffix: Grip thickness
    -2: 2" grip
    -3: 3" grip
    -4: 4" grip

For example, test HFNS-3 features Huck fasteners installed in flat plates (3" grip) by a single installation pass to full swage with no snugging. Test HDS-2 is comprised of Huck LPC fasteners in a 2" grip connection with a deformed middle plate. The installation method is a two pass procedure with an initial snugging pass. A discussion of these tests and the presentation of their results comprises the balance of this chapter.

For all tests performed with the Huck fasteners, a consistent order of installation of the bolts in the test connections was followed. The installation sequence was identical to that used for the conventional A325 fasteners and is shown in Figure 4.1. The order of fastener installation followed the *Bolt Specification* requirement that "tightening shall progress from the most rigid part of the joint to its free edges" [1]. Thus, the first row to be installed (snugged or tightened) consisted of fasteners 4, 5 and 6 while the second row contained fasteners 7, 8, and 9. The last fasteners to be installed were the rows consisting of fasteners 1, 2, and 3, and 10, 11, and 12, respectively.

5.2 FLAT PLATE TESTS

These tests were performed on the plates in their as-delivered condition from the local fabricator, as described in Section 4.1. The flat plate tests were conducted using the single pass installation method. Figure 5.1 shows the installation of a Huck fastener in a test connection. Note the conventional A325 fasteners used for fit-up purposes. These fasteners were used only to align the holes in the plates. No tension was developed in these fasteners.

5.2.1 SINGLE PASS (w/o SNUGGING) INSTALLATION METHOD

This installation method used a single pass to full collar swage to install the Huck fasteners. The results of these tests will be compared to the conventional A325 tests on fasteners in flat plates and installed with a calibrated torque wrench using no snugging. These single pass tests are designated the HFNS series.

5.2.1.1 TEST RESULTS

The presentation of results for the single pass tests, as well as all of the Huck fastener tests, follows the same format. For each test, five figures are presented to detail the observed results. The first is a chart showing the tensions measured in each fastener during the progressive installation of the connection fasteners. From this chart, the load history of each individual bolt can be derived. The second figure is a vertical bar chart indicating the final installed tensions in each bolt and their relationship to the 39 kip minimum preload for a 7/8" diameter A325 fastener. The final three figures are graphical representations of the load histories of three individual fasteners, 4, 8, and 2, in the connections. Each fastener is from a different row in the connection and is chosen as representative of fastener behavior in that part of the connection.

Table 5.1 provides a summary of the pertinent fastener tension results of the HFNS series tests. Included in the table are average values of final fastener tension and fastener tensile load loss. Final fastener tension refers to those loads recorded in the Huck fasteners after the installation of the last fastener in the connection (12 - see Figure 4.1). Tension loss indicates the

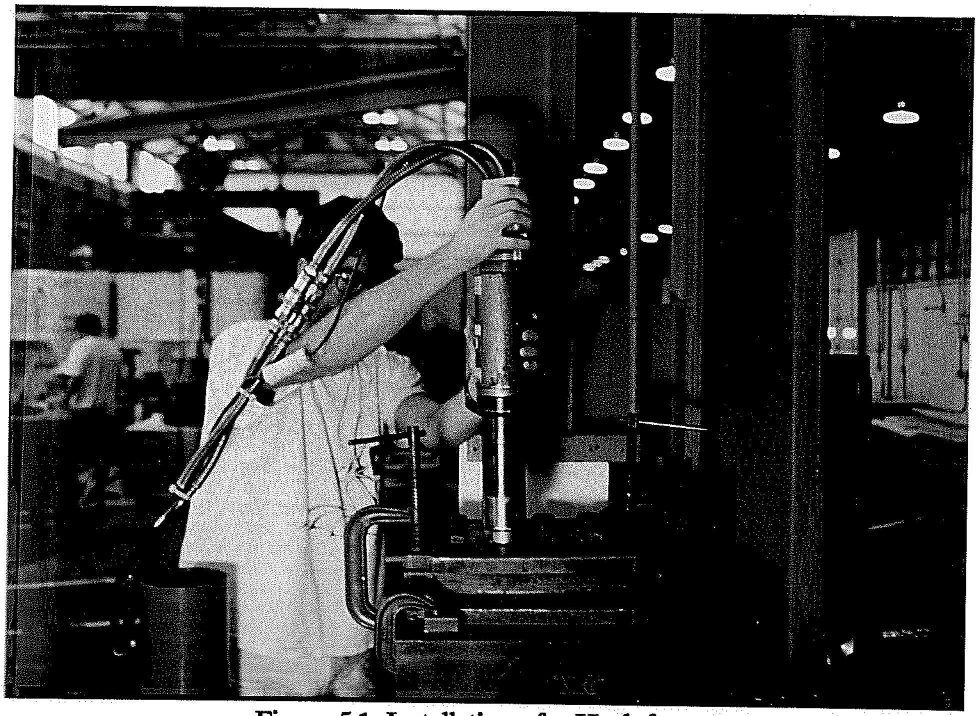


Figure 5.1: Installation of a Huck fastener

Test #	Average Final Fastener Tension	Standard Deviation	Average Fastener Tension Loss	Standard Deviation
HFNS-2	38.4	0.8	0.0	0.5
HFNS-3	39.3	1.5	-0.3	0.9
HFNS-4	40.4	1.6	0.6	0.3

Note: All values in Kips

Table 5.1: Summary of fastener load results for HFNS series tests

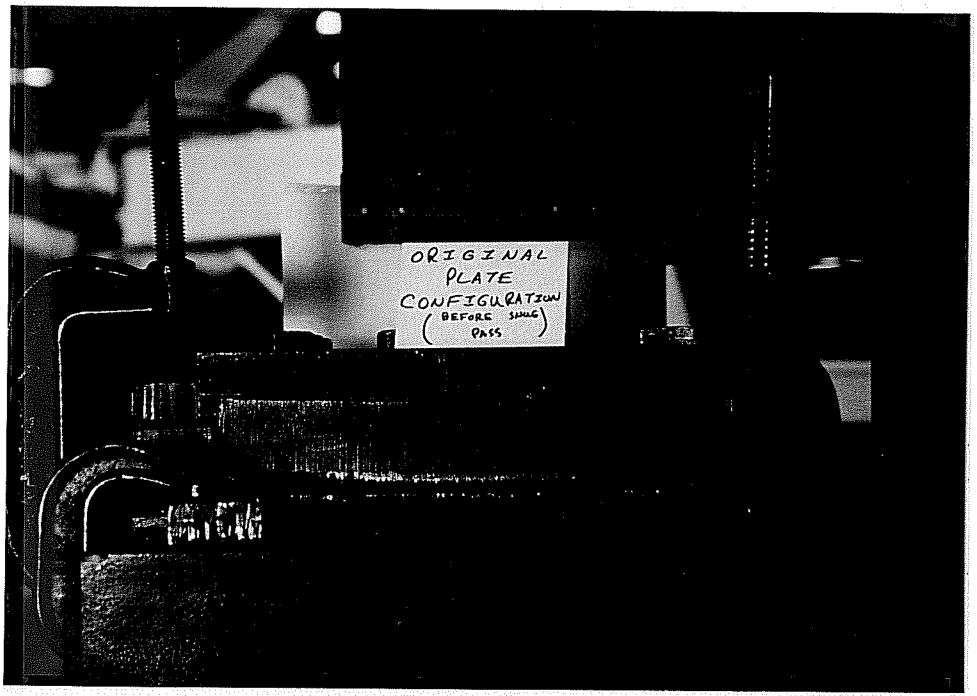


Figure 5.48: Connection plates for test HDS-4 in pre-test condition

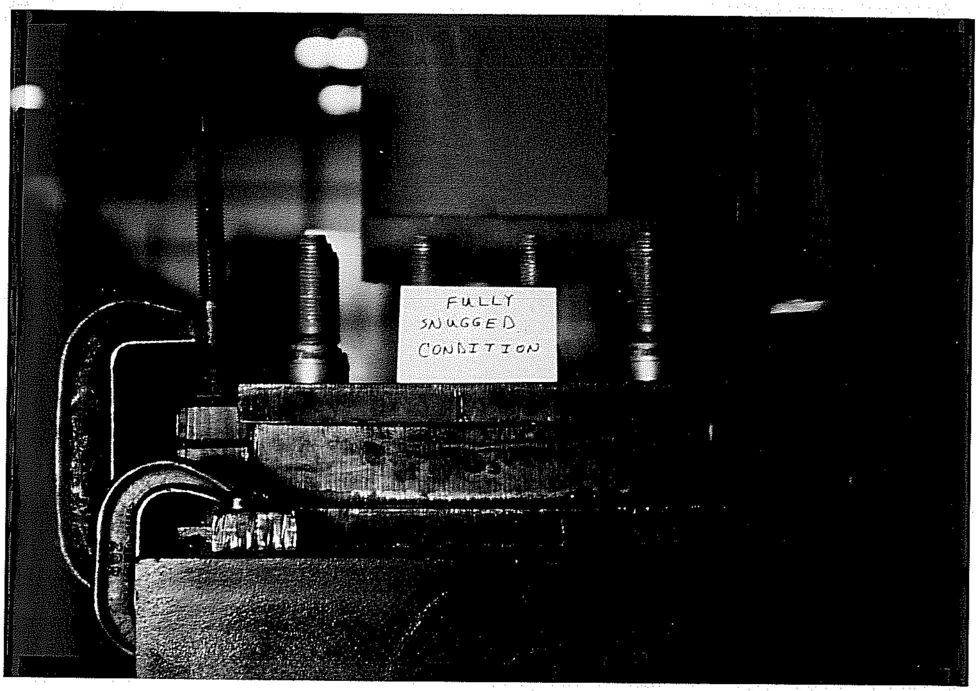


Figure 5.49: Connection plates for test HDS-4 in fully snugged condition

drop in tensile load in each fastener between the initial installation of that fastener and the completion of all fastener installation. Standard deviations for each quantity are also listed.

Test HFNS-2:

Figures 5.2 to 5.6 and Table 5.1 present the results of this test. Figure 5.2 shows that the final average installed tension for the Huck fasteners was 38.4 kips, just below the 39 kip minimum. Also indicated in the figure is the fact that the strain gauges in fasteners 4 and 5 both went bad upon the installation of fastener 6. This was caused by the trapping of the leadwires from both gauges under the head of fastener 6. Care was taken in future tests to avoid this occurrence. As is shown in Table 5.1, little relaxation of fastener tension was noted during the course of the test. Figures 5.4 through 5.6 illustrate the load histories for fasteners 6, 7, and 2. Fasteners 6 and 7 are substituted for the customary fasteners 4 and 8 due to the damage incurred on the leadwires of the strain gauge in fastener 4.

Test HFNS-3:

The results of this 3" grip test are recorded in Figures 5.7 through 5.11 and in Table 5.1. Note that the BTM gauge in fastener #3 went bad early in the test and thus no tensions for that Huck fastener were recorded. After the completion of installation, the average final tension in the remaining 11 fasteners was 39.3 kips, as shown in Figure 5.7. The average change in fastener tension over the course of installation was actually an increase of 0.3 kips (see Table 5.1), as opposed to the previously observed losses of fastener tension. Figure 5.9 illustrates the tensile load gain of fastener 4 while Figures 5.10 and 5.11 show the relative consistency of the tension in fasteners 8 and 2.

Test HFNS-4:

Figures 5.12 to 5.16 and Table 5.1 show the results of test HFNS-4. The average final installed C50L fastener tension for this test was 40.4 kips, the highest of the HFNS series. Some loss of preload was observed for the first row of fasteners installed with decreasing amounts of preload loss in the 2nd installed row and in the exterior rows of fasteners. The average tension loss for all fasteners was 0.6 kips, as noted in Table 5.1. Figures 5.14 through 5.16 show the load histories for fasteners 4, 8, and 2.

5.3 DEFORMED PLATE TESTS

Plate deformation in these tests was identical to those described in Section 4.3 for the conventional A325 fastener tests (3mm midspan deflection of the middle plate). Verification of

Fastener Number

Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	37.5	0	0.0	0	-0	0	0.0	-0	-0	0	0	0
5.0	37.9	39.4	0	0	0.0	0	0.0	-0	0	0	0	0
6.0	37.4	39.4	39.0	0	0	0	0.0	0.0	0.0	0.0	0	0.0
7.0	38.3	39.5	38.7	38.2	0	0	0	0.0	0.0	0	0	0
8.0	38.0	39.7	38.7	38.5	39.2	0	-0	-0	-0	0.0	0.0	-0
9.0	38.0	39.5	38.9	38.2	39.5	39.1	0.0	0.0	0.0	0	0	0.0
1.0	B.G	B.G	38.8	38.1	39.2	38.7	38.7	-0	-0	0	0	0.0
2.0	B.G	B.G	38.9	38.0	39.2	38.5	38.4	38.1	-0	0	0	-0
3.0	B.G	B.G	39.7	38.0	39.2	38.4	38.4	38.0	38.2	0.1	0	0
10.0	B.G	B.G	39.5	38.9	39.4	38.2	38.2	37.8	37.6	37.9	-0	-0
11.0	B.G	B.G	39.5	38.9	40.0	38.4	38.2	37.8	37.6	38.0	38.3	-0
12.0	B.G	B.G	39.4	38.8	39.9	39.1	38.2	37.7	37.5	37.9	38.2	37.2

Tension in Kips

Average Fastener Tension = 38.4 Kips

28 Grip Huck C50L Fasteners
2" Grip
Flat Plates
One Pass Installation
(No Snugging)

1	4	7	10
2	5	8	11
3	6	9	12

Fastener Numbers

Figure 5.2: Fastener Tensions for Test HFNS-2

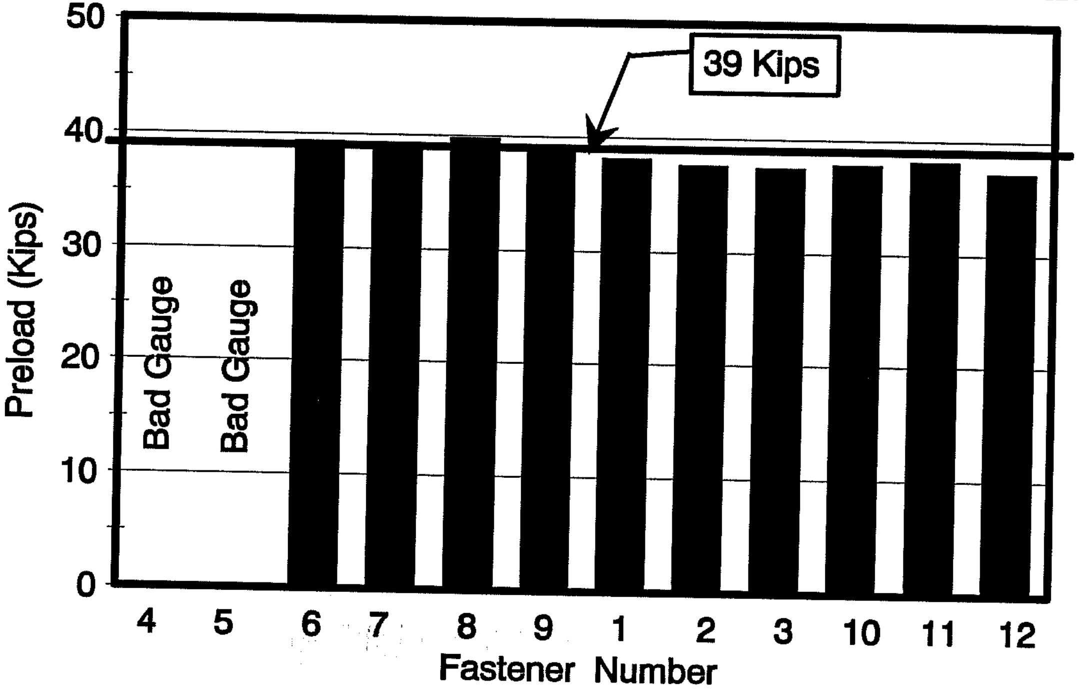


Figure 5.3: Final Installed Tensions for Test HFNS-2

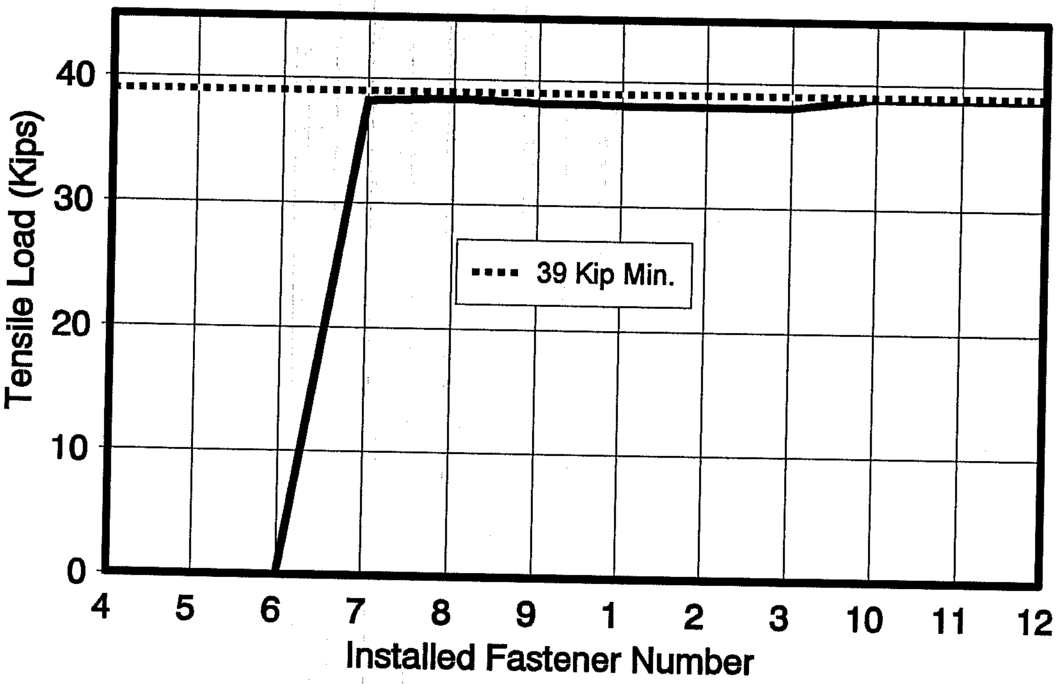


Figure 5.4: Tensile Load History for Fastener #7 - Test HFNS-2

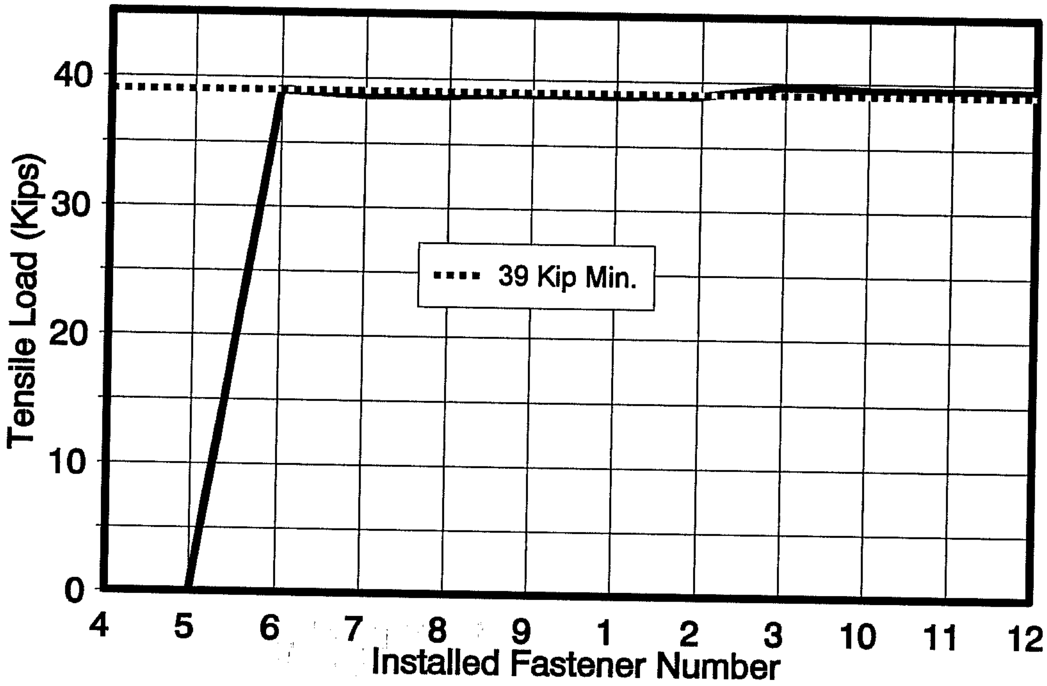


Figure 5.5: Tensile Load History for Fastener #6 - Test HFNS-2

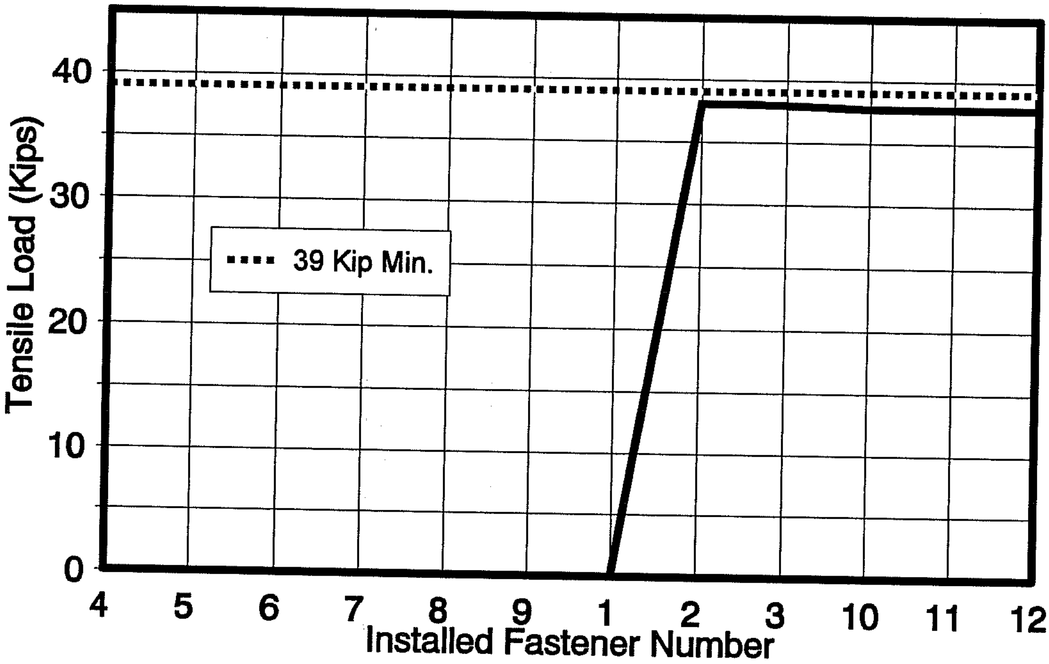


Figure 5.6: Tensile Load History for Fastener #2 - Test HFNS-2

Fastener Number

Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	37.8	0	0	0.1	0.1	0.1	-0	0.1	0.1	0.1	0.1	0
5.0	38.1	40.5	0	0.1	0.1	0.1	0	0.1	-0	0.1	0.1	0
6.0	37.7	40.4	36.5	0.1	0	0	-0	0.1	0.5	0.1	0.1	0
7.0	38.6	41.0	36.2	40.5	0	0	-0	0.1	12.7	0	0.1	0
8.0	38.7	41.1	36.5	40.4	38.6	0	-0	0	8.8	0.0	0.1	0.0
9.0	38.7	41.2	37.2	40.4	38.1	39.1	0	0.1	B.G.	0.1	0.1	0
1.0	39.9	42.2	37.5	40.4	38.1	38.7	38.4	0.2	B.G.	0.2	0.3	0.2
2.0	39.9	42.5	38.0	40.4	38.1	38.6	38.3	40.3	B.G.	0.2	0.2	0.1
3.0	39.8	42.5	38.3	40.3	38.0	38.5	38.2	40.3	B.G.	0.1	0.2	0.1
10.0	39.6	42.4	38.1	40.7	38.4	38.4	38.2	40.1	B.G.	38.7	0.1	0
11.0	39.5	42.3	38.0	40.8	38.3	38.6	38.1	40.1	B.G.	38.3	37.5	0
12.0	39.6	42.2	38.0	40.8	38.4	38.8	38.1	40.1	B.G.	38.2	37.0	40.9

Tension in Kips

Average Fastener Tension = 39.3 Kips

44 Grip Huck C50L Fasteners
3" Grip
Flat Plates
One Pass Installation
(No Snugging)

1	4	7	10
2	5	8	11
3	6	9	12

Fastener Numbers

Figure 5.7: Fastener Tensions for Test HFNS-3

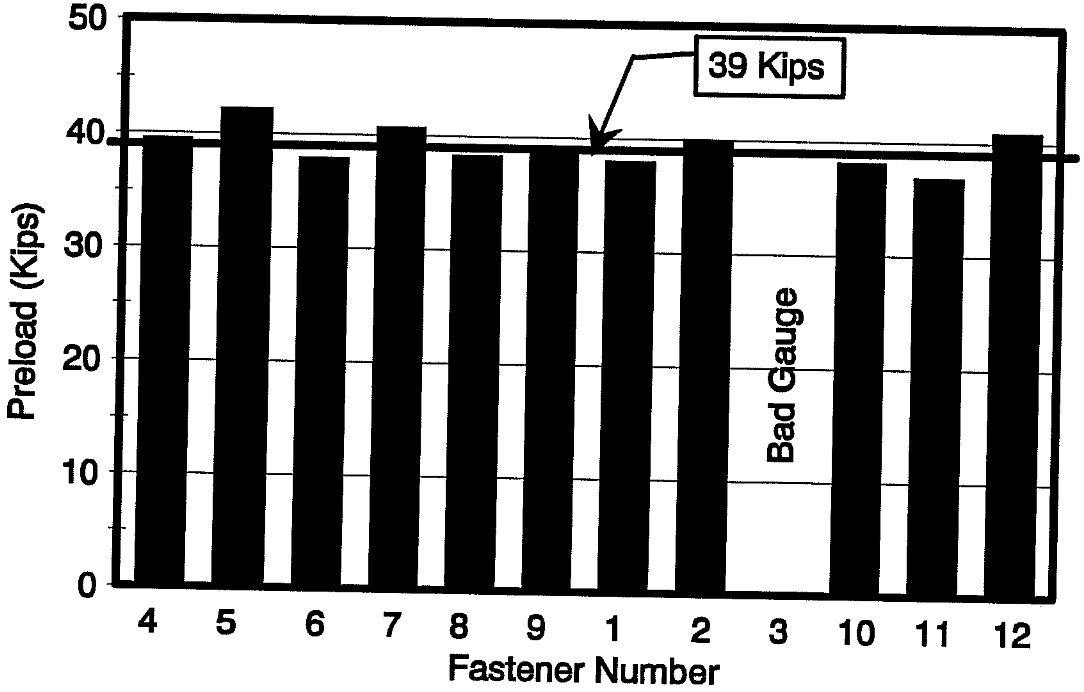


Figure 5.8: Final Installed Tensions for Test HFNS-3

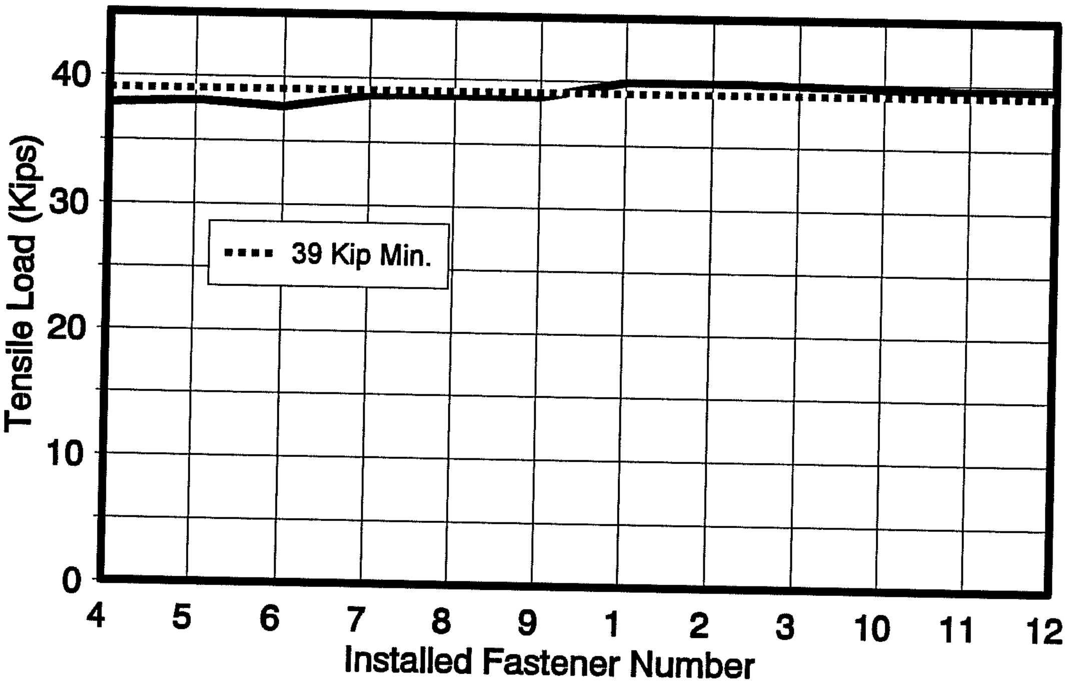


Figure 5.9: Tensile Load History for Fastener #4 - Test HFNS-3

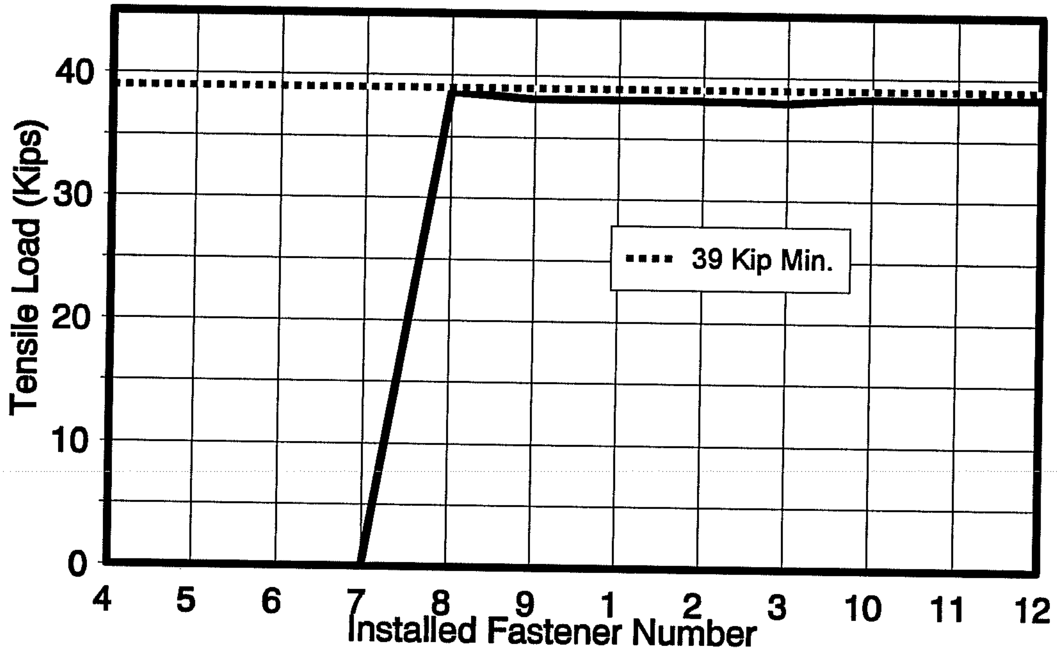


Figure 5.10: Tensile Load History for Fastener #8 - Test HFNS-3

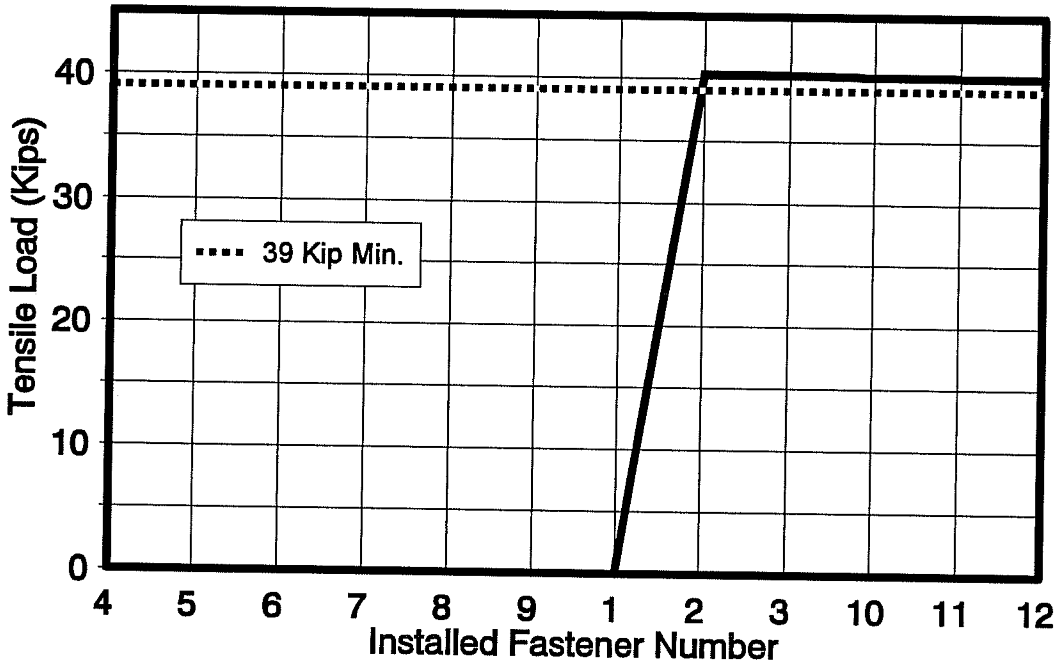


Figure 5.11: Tensile Load History for Fastener #2 - Test HFNS-3

Fastener Number

Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	41.0	-0.1	-0.1	0	0	-0.1	-0.1	-0.1	-0	-0.1	-0.1	-0.1
5.0	40.2	39.4	-0.3	-0	-0.2	-0	-0	0.1	-0	0.0	-0	0.0
6.0	39.9	37.9	43.1	-0	0	0	0	-0.1	-0.1	0.0	0.1	0.2
7.0	39.4	38.5	43.2	37.6	0.3	0.1	0	-0.1	-0	0.0	0.1	0.2
8.0	39.5	37.9	42.9	37.0	42.0	-0.1	0	0.1	-0.1	-0.1	-0.1	0.0
9.0	39.2	37.7	42.1	37.1	41.1	42.4	-0	-0.4	-0.2	0	0.1	0.1
1.0	39.5	38.0	42.2	37.1	41.1	42.2	41.0	-0.5	-0	-0	0.1	0.1
2.0	39.8	38.4	42.6	37.1	41.3	42.0	40.7	41.6	-0.1	-0.2	-0.1	0
3.0	40.1	38.7	42.8	37.1	41.4	42.1	40.7	41.4	38.9	-0.2	-0.1	0
10.0	39.8	38.4	42.5	36.8	41.4	42.3	40.7	41.1	38.7	41.6	0.0	0.1
11.0	40.2	38.9	42.9	37.0	41.9	42.4	40.7	41.4	38.7	41.4	41.5	0.1
12.0	39.7	38.3	42.5	36.9	41.4	42.2	40.7	41.1	38.6	41.4	41.1	40.7

Tension in Kips

Average Fastener Tension = 40.4 Kips

60 Grip Huck C50L Fasteners
4" Grip
Flat Plates
One Pass Installation
(No Snugging)

1	4	7	10
2	5	8	11
3	6	9	12

Fastener Numbers

Figure 5.12: Fastener Tensions for Test HFNS-4

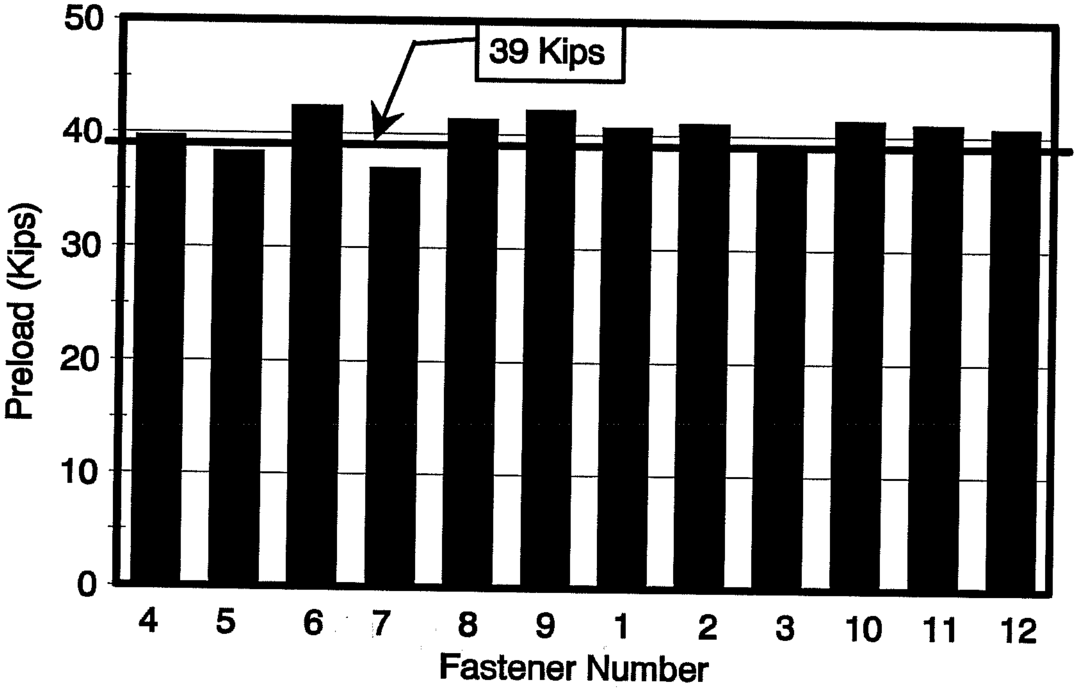


Figure 5.13: Final Installed Tensions for Test HFNS-4

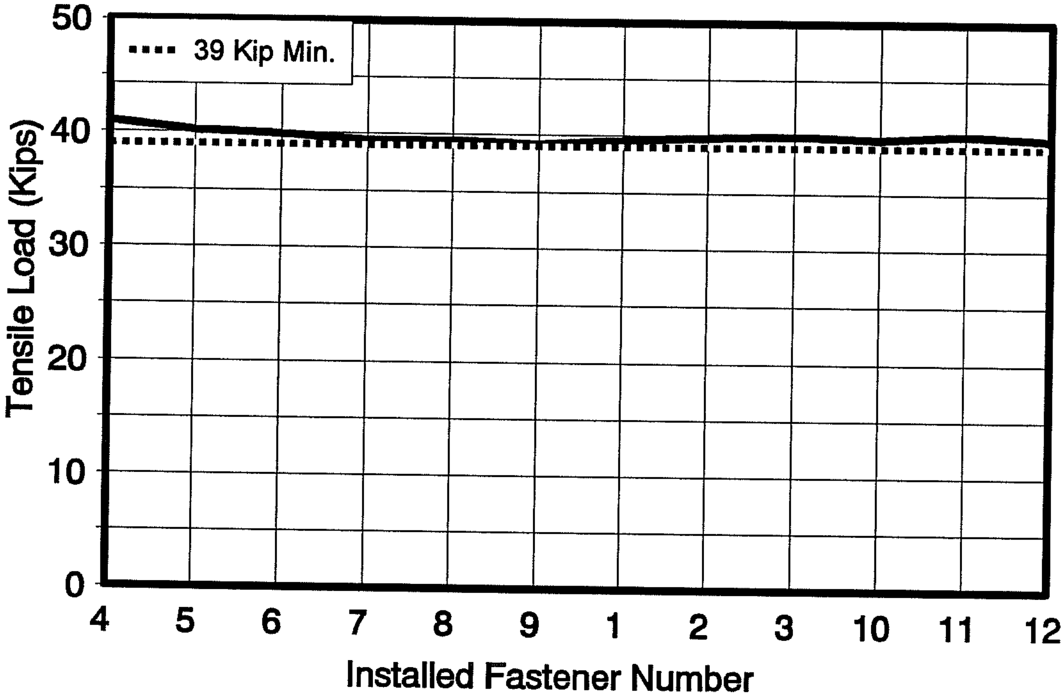


Figure 5.14: Tensile Load History for Fastener #4 - Test HFNS-4

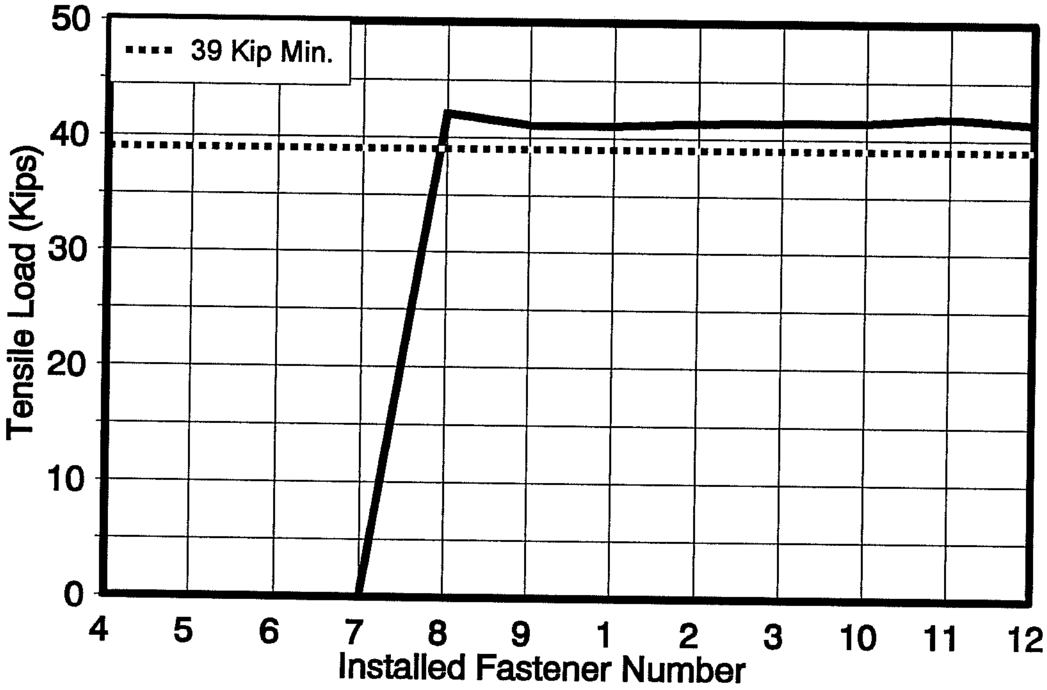


Figure 5.15: Tensile Load History for Fastener #8 - Test HFNS-4

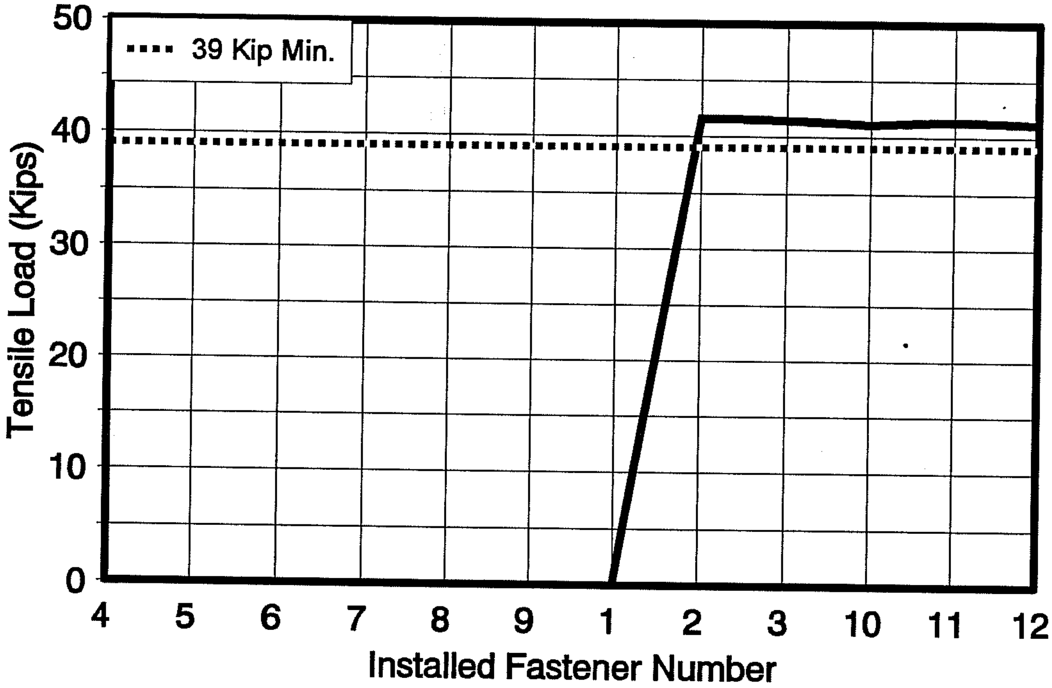


Figure 5.16: Tensile Load History for Fastener #2 - Test HFNS-4

plate deflection (inner plate) and plate flatness (outer plates) was conducted in the same manner as outlined in Section 4.3.

The deformed plate tests were conducted on all three grip lengths (2", 3", and 4") and Huck fastener installation was conducted by the following two methods:

1.) Single installation pass (no snugging)
2.) Dual installation passes (with initial snugging pass)

5.3.1 SINGLE PASS (w/o SNUGGING) INSTALLATION METHOD

This installation method used a single pass to full collar swage to install the Huck fasteners. These results will be compared to the conventional A325 tests on fasteners in deformed plates and installed by the calibrated wrench method with no snugging (CDCWNS series). These tests are reported as the HDNS series.

5.3.1.1 TEST RESULTS

Table 5.2 provides a summary of the pertinent fastener tension results of the HDNS series tests. Included in the table are average values of final fastener tension and fastener tensile load loss in both the interior and exterior rows of fasteners. Final fastener tension refers to those loads recorded in the Huck fasteners after the installation of the last fastener in the connection (#12 - see Figure 4.1). Tension loss indicates the drop in tensile load in each fastener between the initial installation of the fastener and the completion of all fastener installation. Standard deviations for each quantity are also listed.

Test HDNS-2:

Figures 5.17 through 5.21 and Table 5.2 present the results of this connection test. As is shown in Figure 5.17, the average final installed fastener tension was 38.9 kips. Minimal amounts of preload loss were noted for the connection fasteners. Table 5.2 shows that the small load relaxations that did occur were found in the fasteners of the interior rows of the connection. The average losses of preload in the interior and exterior Huck fasteners were 0.5 and 0.0 kips, respectively. The load histories of typical interior and exterior fasteners are shown in Figures 5.19 to 5.21.

Test HDNS-3:

The results of test HDNS-3 are listed in Figures 5.22 to 5.26 and in Table 5.2. The average installed fastener tension for this test was 32.5 kips, well beneath the 39 kip minimum specified value. During the installation sequence, the interior fasteners lost a significant amount

Test #	Average Final Fastener Tension	Standard Deviation	Average Fastener Tension Loss In Interior Rows	Standard Deviation	Average Fastener Tension Loss In Exterior Rows	Standard Deviation
HDNS-2	38.9	1.6	0.5	0.7	0.0	0.2
HDNS-3	32.5	8.0	13.9	5.8	0.6	1.1
HDNS-4	31.5	10.7	20.2	6.0	2.2	1.2

Note: All values in Kips

Table 5.2: Summary of fastener load results for HDNS series tests

of preload with the average amount of lost tension being 13.9 kips (see Table 5.2). The exterior fasteners retained most of their tensile loads with the average loss for the these fasteners being 0.6 kips. Figures 5.24 and 5.25 illustrate the relaxation of tension in two interior fasteners (4 and 8) while Figure 5.26 shows the relatively constant load levels maintained in a typical exterior fastener (2).

Test HDNS-4:

Figures 5.27 to 5.31 and Table 5.2 show the results of this 4" grip test. Figure 5.27 indicates that the average final installed tension for the connection is only 31.5 kips. The interior rows of fasteners experienced large reductions in preload during installation with the average amount of loss being 20.2 kips (see Table 5.2). The average preload loss for the exterior rows was only 2.2 kips. The difference in the magnitudes of load relaxation between the interior and exterior fasteners is best shown by the comparison of Figures 5.29 through 5.31 which show the load histories of two interior fasteners (4 and 8) and an exterior fastener (2).

Fastener Number

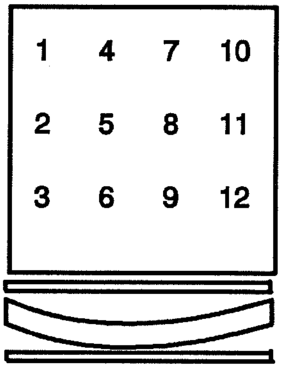
Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	38.4	0.1	0	0	0	0.1	0	0	0	0	0	0.1
5.0	37.9	36.8	-0	-0	-0	-0.1	-0	-0	-0.1	-0.1	-0	-0.1
6.0	37.9	36.6	40.0	0.1	0	0	0.1	0	0	0	0.1	0
7.0	38.5	36.8	39.8	38.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
8.0	38.2	36.9	40.0	36.5	40.2	0.1	0	0	0	0	0	0
9.0	38.1	36.8	40.2	36.4	39.4	40.4	0	0	0	0	0	0
1.0	38.5	36.6	39.7	36.3	39.3	39.8	37.9	-0	-0	-0	-0	0.0
2.0	38.4	36.9	39.2	36.2	39.1	39.7	38.1	37.9	0	0	0	0
3.0	38.4	36.9	39.6	36.2	39.1	39.6	38.0	38.1	43.2	0.1	0	0.1
10.0	38.4	36.9	39.5	36.4	39.3	39.5	38.0	37.9	42.8	39.1	0.1	0.1
11.0	38.4	36.8	39.4	36.4	39.7	39.5	38.0	37.9	42.8	39.2	38.4	0.1
12.0	38.5	36.9	39.5	36.5	39.8	40.1	38.1	38.0	42.8	39.3	38.5	39.4

Tension in Kips

Average Fastener Tension = 38.9 Kips

28 Grip Huck C50L Fasteners
2" Grip
Deformed Plates
One Pass Installation
(No Snugging)



Fastener Numbers

Figure 5.17: Fastener Tensions for Test HDNS-2

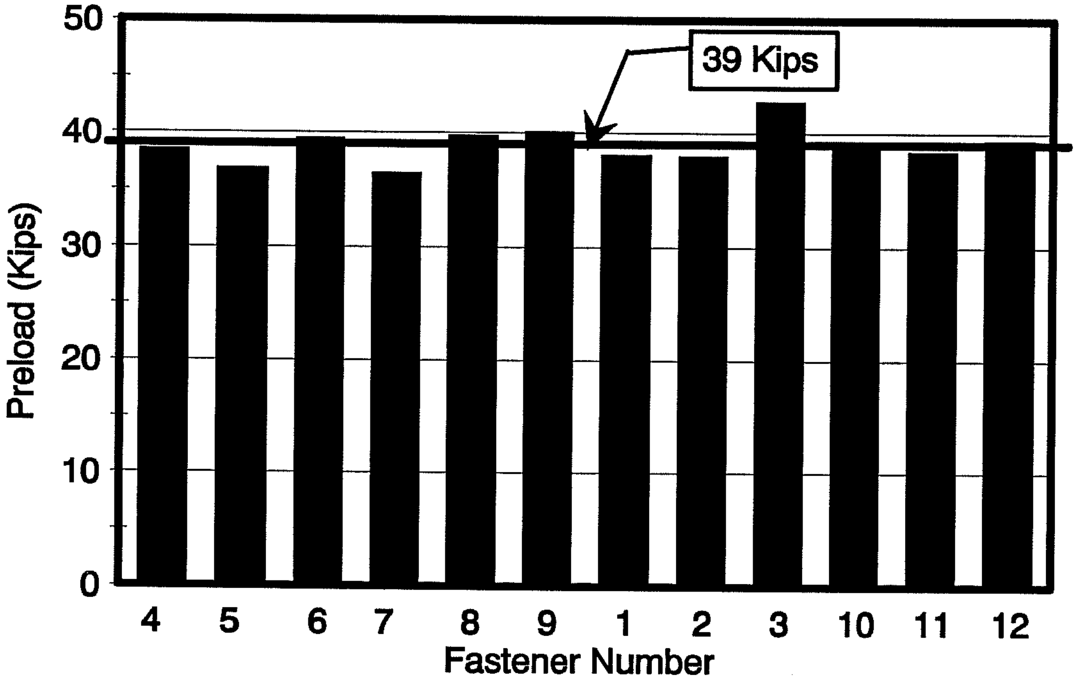


Figure 5.18: Final Installed Tensions for Test HDNS-2

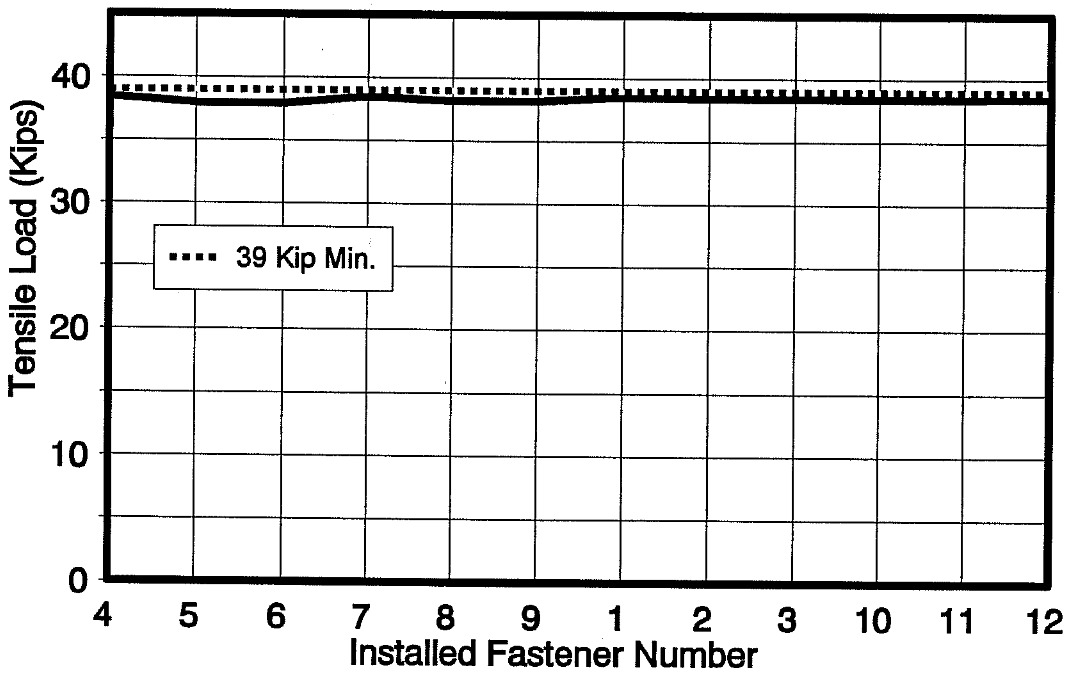


Figure 5.19: Tensile Load History for Fastener #4 - Test HDNS-2

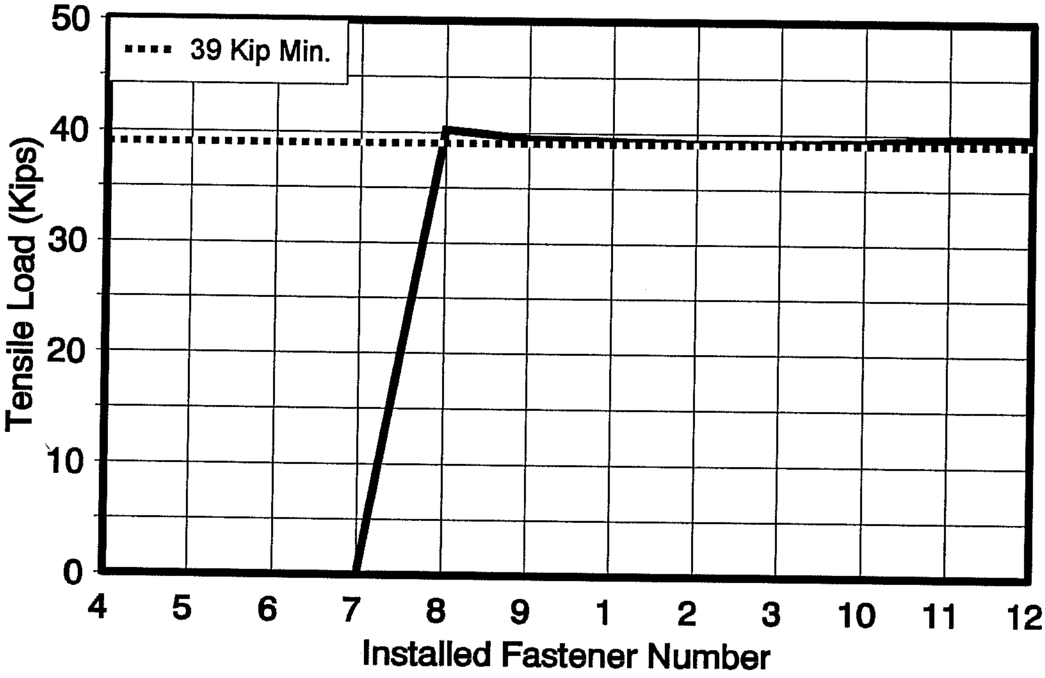


Figure 5.20: Tensile Load History for Fastener #8 - Test HDNS-2

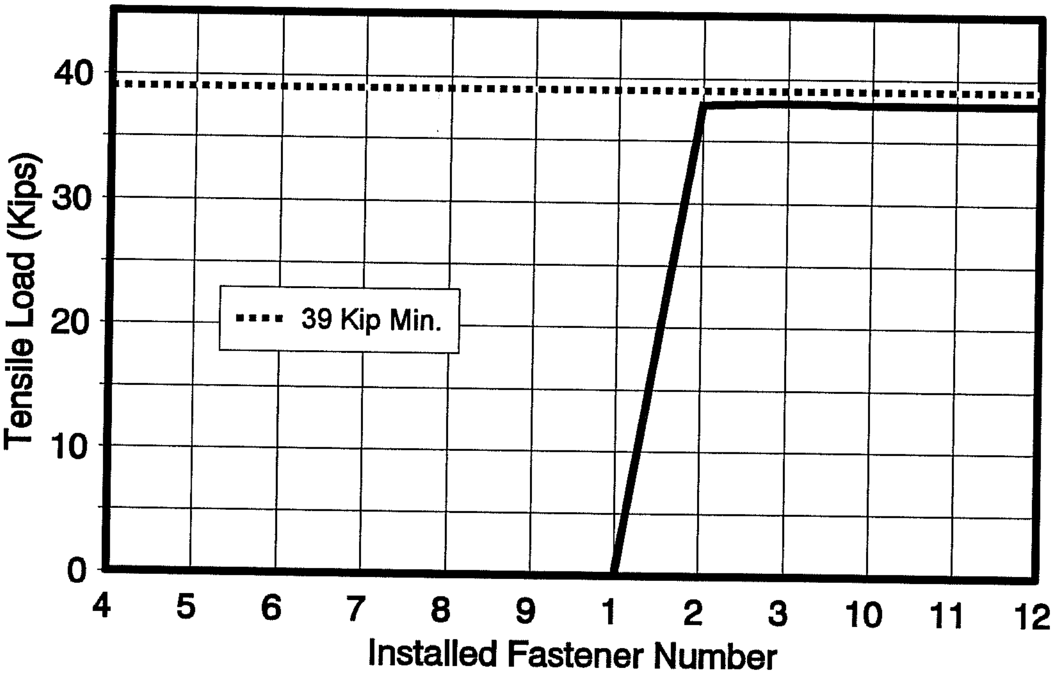


Figure 5.21: Tensile Load History for Fastener #2 - Test HDNS-2

Fastener Number

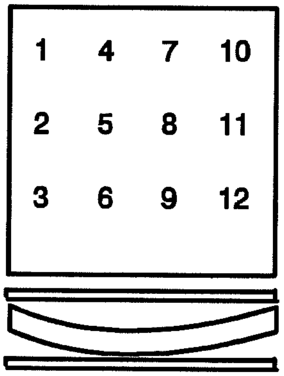
Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	36.7	-0	0	-0	-0.1	0	-0	-0	-0	-0	-0	-0
5.0	25.2	40.7	-0.1	-0.2	-0.3	-0.2	-0.2	-0.1	-0.2	-0.1	-0.2	-0.1
6.0	25.8	31.5	39.6	-0	-0.1	0.1	-0	-0	-0	-0	0.0	0.1
7.0	26.3	31.4	39.5	40.3	-0.2	-0.1	-0.1	-0	-0.1	0.1	-0.1	0.1
8.0	28.6	32.3	40.7	25.6	39.7	-0.1	0	-0.1	0.1	0.1	0	0.1
9.0	28.6	34.2	40.5	24.0	27.1	42.2	-0.1	-0.1	-0.1	-0.1	-0.1	0.8
1.0	24.4	29.8	36.4	23.8	27.0	42.0	40.8	-0.1	-0	0.1	-0	0.9
2.0	24.9	29.4	31.9	23.8	27.0	42.3	41.0	40.4	0	0.1	-0	1.0
3.0	25.0	30.2	28.5	23.8	27.2	42.8	41.1	37.8	42.3	0	0.1	1.0
10.0	25.2	30.3	28.7	15.9	21.1	39.7	40.9	37.9	41.7	38.1	-0.1	1.0
11.0	25.2	30.4	28.8	16.1	20.2	37.0	40.8	37.8	41.6	38.2	33.6	2.2
12.0	25.2	30.4	29.0	16.1	20.6	34.8	40.8	37.8	41.6	38.2	33.8	41.2

Tension in Kips

Average Fastener Tension = 32.5 Kips

44 Grip Huck C50L Fasteners
3" Grip
Deformed Plates
One Pass Installation
(No Snugging)



Fastener Numbers

Figure 5.22: Fastener Tensions for Test HDNS-3

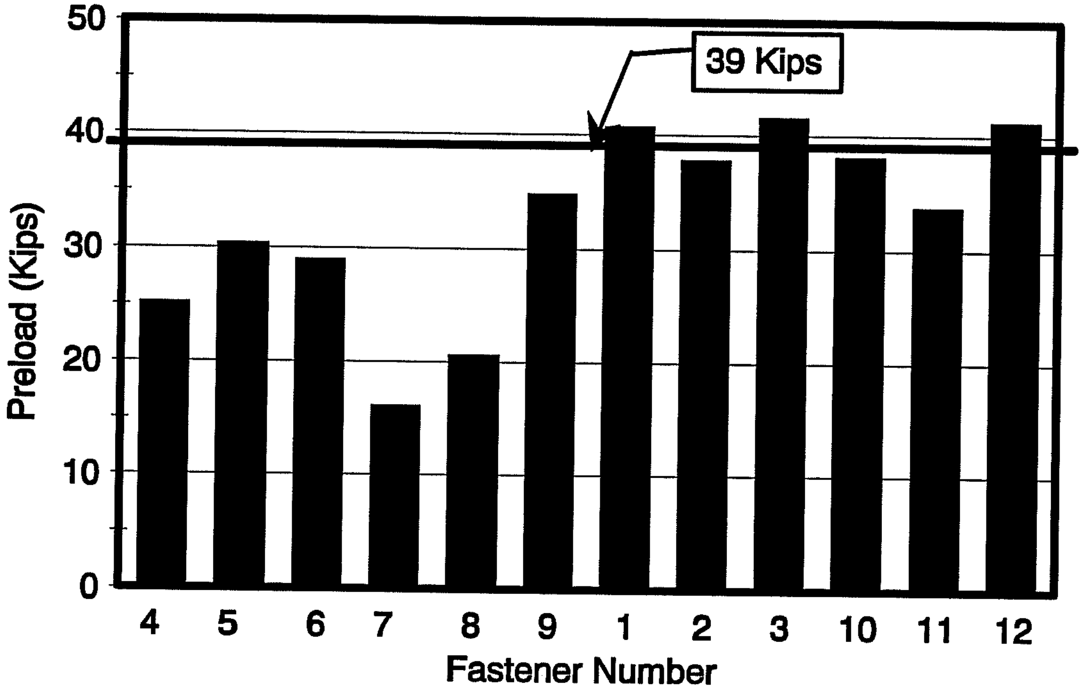


Figure 5.23: Final Installed Tensions for Test HDNS-3

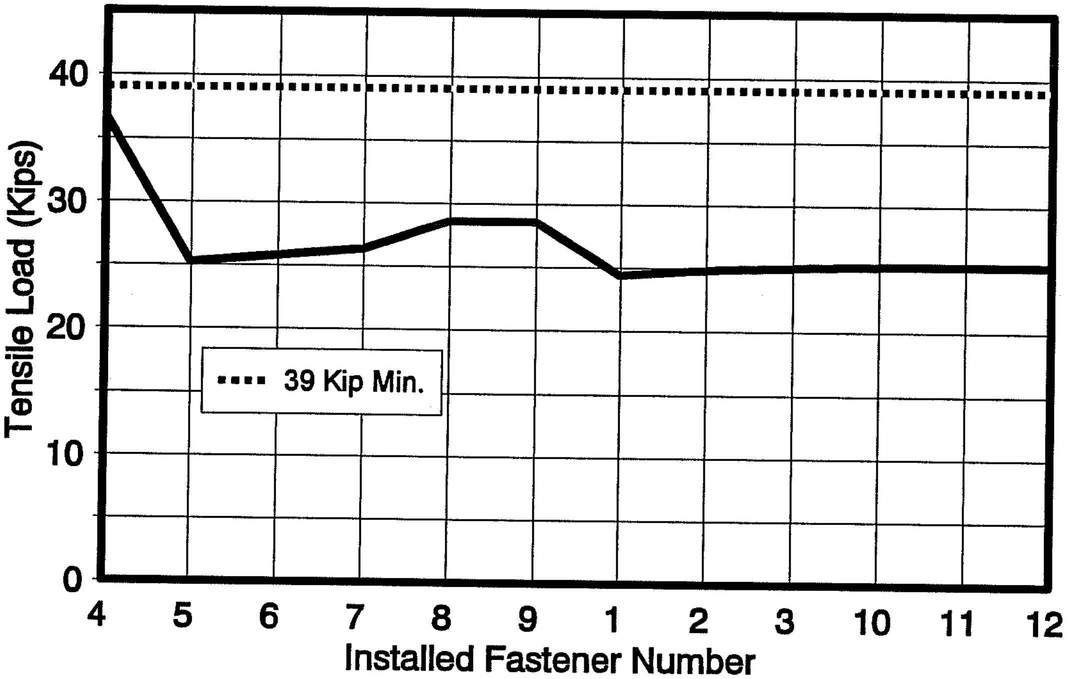


Figure 5.24: Tensile Load History for Fastener #4 - Test HDNS-3

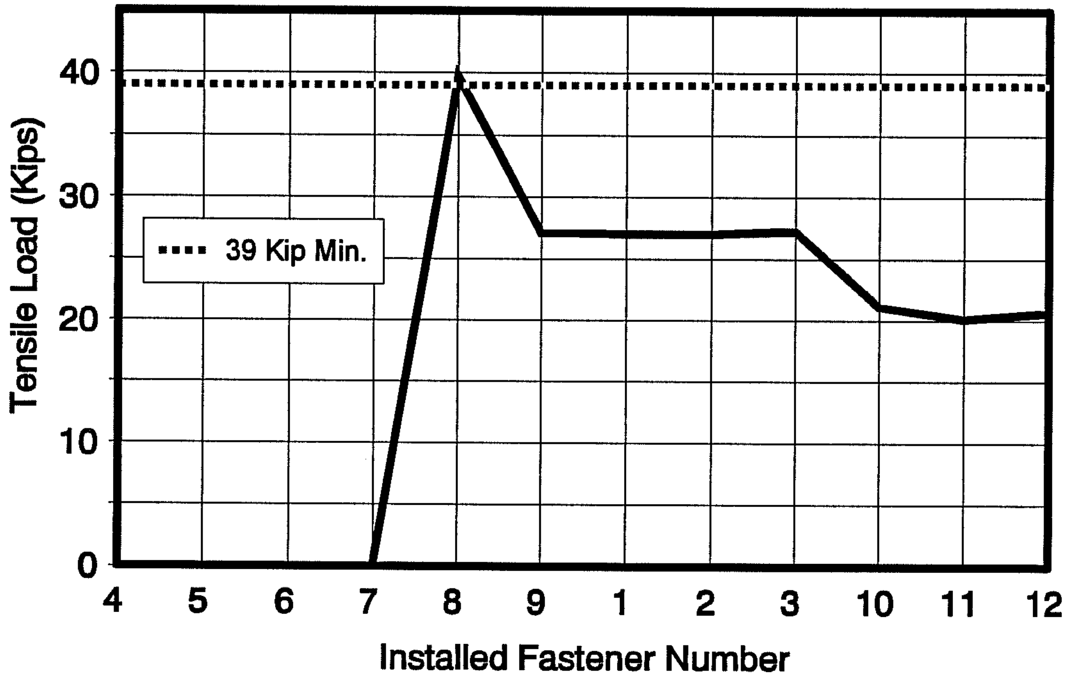


Figure 5.25: Tensile Load History for Fastener #8 - Test HDNS-3

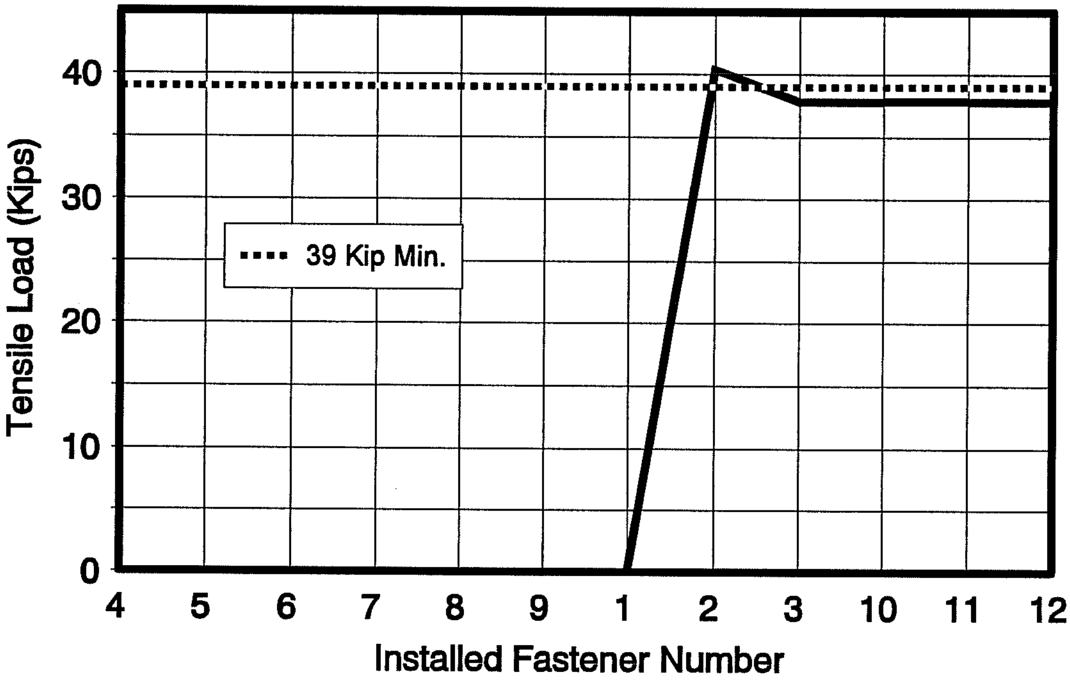


Figure 5.26: Tensile Load History for Fastener #2 - Test HDNS-3

Fastener Number

Tightening Order

	4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
4.0	39.7	0.0	-0.1	0	0.1	-0	0	-0.1	-0	-0.1	-0	0.1
5.0	17.2	41.3	-0	0.1	0.2	0	0	-0	0	0	0.1	0.2
6.0	17.9	25.5	45.9	0.1	0.1	0.1	-0.1	-0.1	-0.1	-0.1	-0	0.2
7.0	19.8	26.6	44.6	41.5	0.1	0.0	-0	-0.1	0.0	-0	0.1	0.3
8.0	24.9	30.1	45.2	27.4	43.7	0.0	-0	-0	-0	0.0	0	0.3
9.0	27.0	34.8	43.2	25.4	32.8	43.1	0.0	0.0	-0.1	0	0	0.3
1.0	11.8	23.6	37.8	28.0	34.2	43.9	41.5	-0	0	-0	0.1	0.5
2.0	12.7	20.5	32.9	28.0	34.7	44.9	37.5	44.3	0	0.0	0.1	0.6
3.0	12.6	21.3	32.4	27.8	34.6	45.1	37.5	41.6	42.6	-0.1	-0	3.6
10.0	14.2	21.9	33.1	11.6	24.9	37.3	37.5	41.5	42.3	39.5	-0.1	3.9
11.0	14.4	22.1	33.7	12.5	22.3	30.9	37.5	41.6	42.3	38.1	41.3	4.5
12.0	14.2	22.1	33.8	12.5	22.5	29.1	37.5	41.5	42.2	38.1	39.1	45.3

Tension in Kips

Average Fastener Tension = 31.5 Kips

60 Grip Huck C50L Fasteners
4" Grip
Deformed Plates
One Pass Installation
(No Snugging)

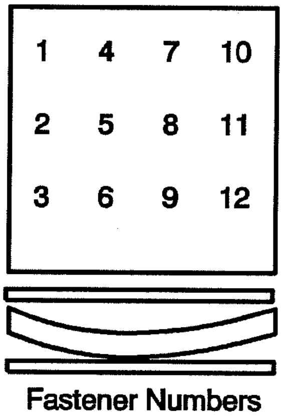


Figure 5.27: Fastener Tensions for Test HDNS-4

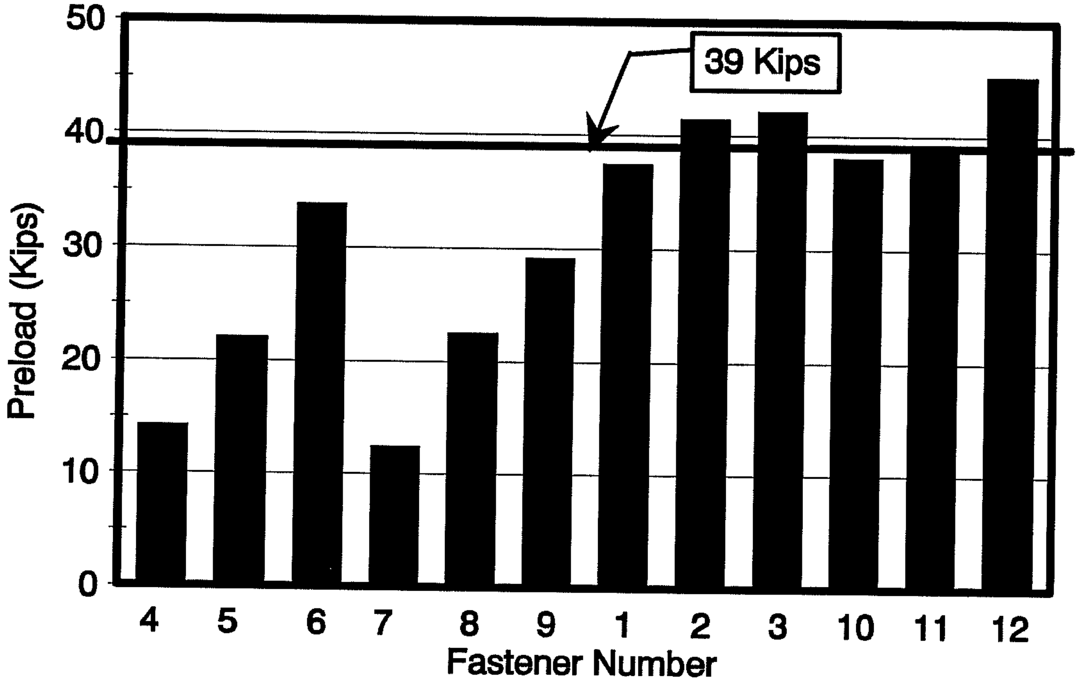


Figure 5.28: Final Installed Tensions for Test HDNS-4

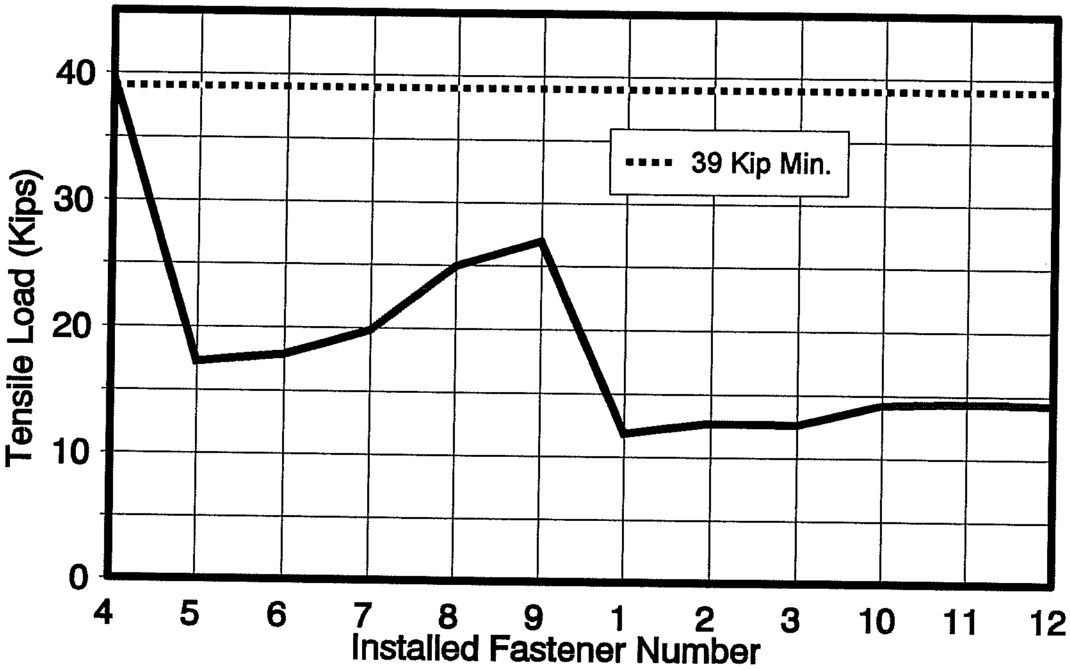


Figure 5.29: Tensile Load History for Fastener #4 - Test HDNS-4

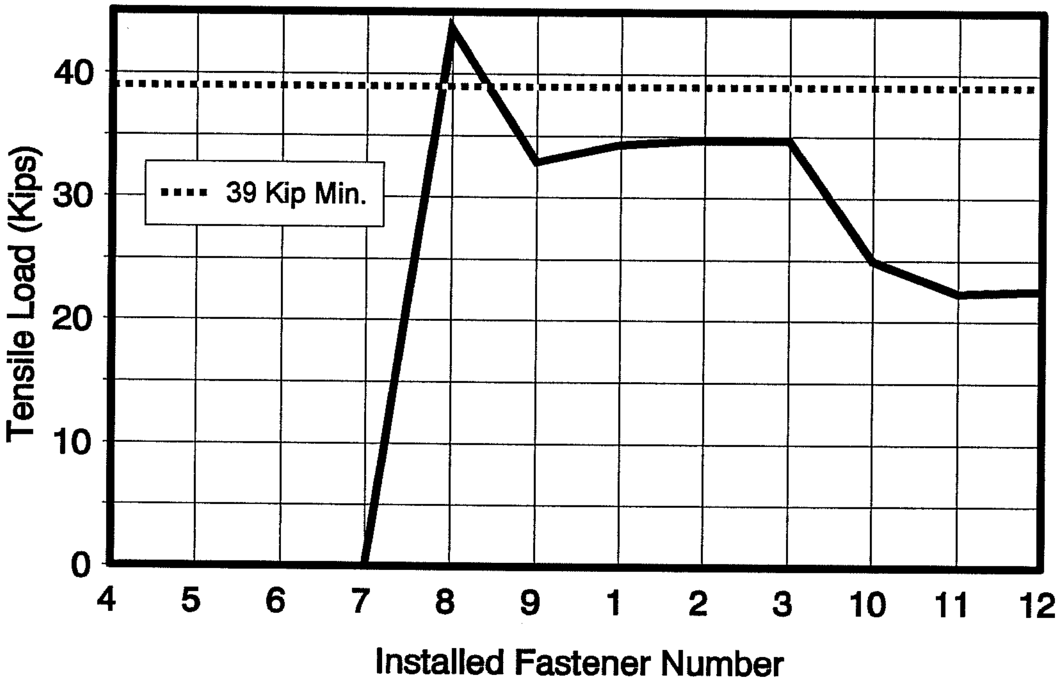


Figure 5.30: Tensile Load History for Fastener #8 - Test HDNS-4

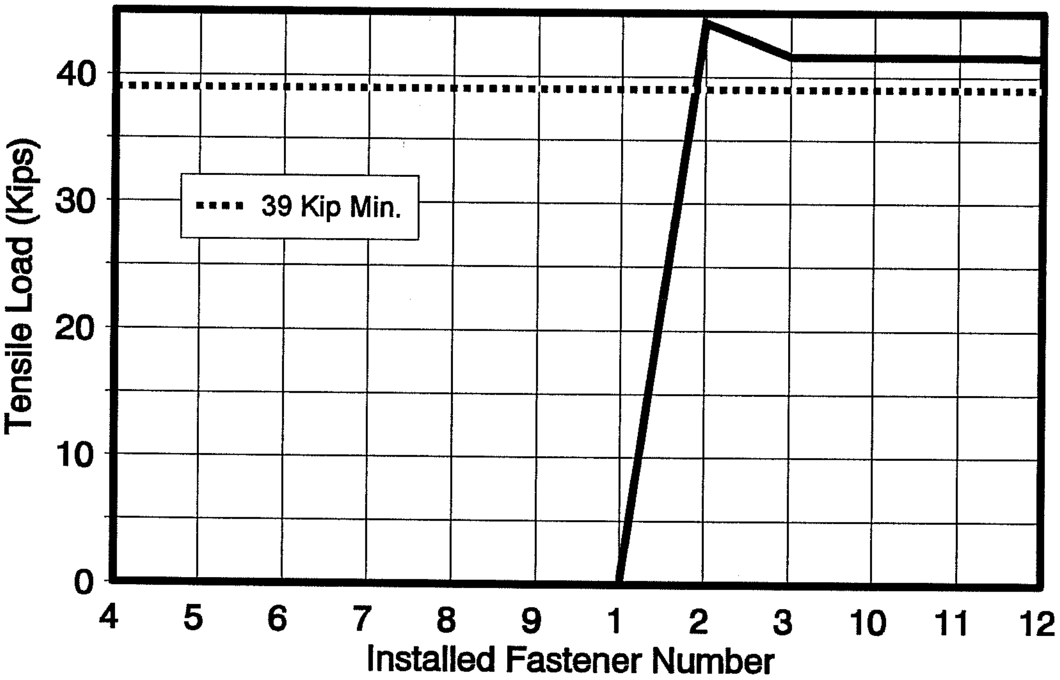


Figure 5.31: Tensile Load History for Fastener #2 - Test HDNS-4

5.3.2 TWO PASS (w/SNUGGING) INSTALLATION

These tests were performed using a two pass installation technique in which the initial pass was intended to snug each fastener prior to the final full swaging pass. The target snug load was about 12 kips which was specified by Huck as being their recommended snug load level for the LC collar. At about the 12 kip level only a small portion of the collar is swaged. These test results will be compared with those of the conventional A325 fastener CDCW series tests.

The snug load was achieved in each fastener by reducing the hydraulic pressures to the installation tool (both pull and return). These pressures were varied by changing the settings on the outlet valves from the pump to the lead hoses on the installation tool. In this manner, the pressures could be reduced to levels that would not cause fracture of the lock-pin break neck and yet cause partial swaging of the collar onto the pin. Upon reaching the full pressure allowed by the valve settings, the pump would emit a high-pitched whine. At the onset of this noise, the trigger on the installation tool was released and the snugging operation ceased. The valve settings and the corresponding induced tensile loads in the lock-pins were determined through trial-and-error by installing sample fasteners in the Skidmore-Wilhelm bolt tension indicator. Figure 5.32 shows the 2" grip connection (test HDS-2) with snugged Huck fasteners. Note the fully swaged fasteners on the left and the snugged fasteners on the right.

These tests are designated the HDS series.

5.3.2.1 TEST RESULTS

Tables 5.3 and 5.4 provide a summary of the pertinent fastener tension results of the HDS series tests. Included in the tables are average values of final fastener tension and fastener tensile load loss in both the interior and exterior rows of fasteners. These losses are shown for both the snugging and final swaging passes. Also shown are the average initial snug tensions for the fasteners. Final fastener tension refers to those loads recorded in the Huck fasteners after the final installation (full collar swage) of the last fastener in the connection (#12 - see Figure 4.1). Initial snug tensions are those measured in each fastener immediately after the snugging of that particular fastener. Tension loss indicates the drop in tensile load in each fastener between the initial installation (full or partial swage) of the fastener and the completion of the installation sequence (either snugging or full swage). Standard deviations for each quantity are also listed.

Test HDS-2:

Figures 5.33 through 5.37 and Tables 5.3 and 5.4 report the results of this 2" grip test. Table 5.4 shows that the average final installed fastener tension was 34.6 kips. The average initial

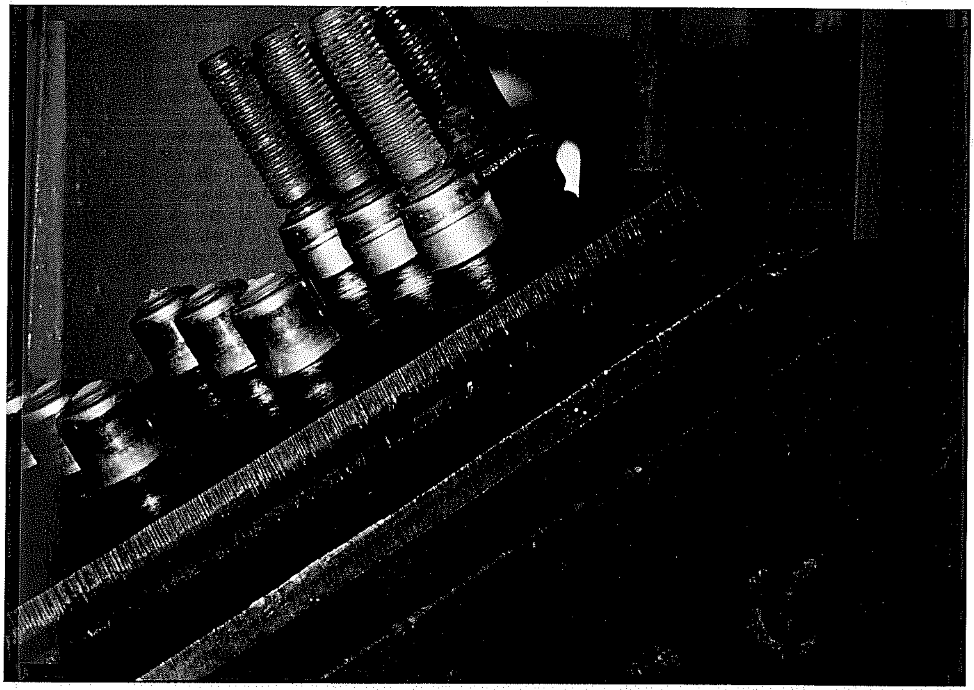


Figure 5.32: Connection with partially swaged Huck fasteners

snug tension for the fasteners was 11.2 kips. During the snugging pass, an average of 4.3 kips of tension was lost from the fasteners in the interior of the connection while the exterior fasteners lost an average of 1.1 kips. The 4.3 kips of lost load in the interior fasteners represents over 1/3 of the target 12 kip snug load. In the course of the full swaging installation pass, the average interior fastener loss fell to 2.7 kips while the average loss in the exterior fasteners remained at about 1.2 kips. Figures 5.35 to 5.37 illustrate the tension losses for three sample fasteners, 4 and 8 (interior of connection) and 2 (exterior of connection).

Test HDS-3:

The results of this test can be seen in Figures 5.38 through 5.42 and in Tables 5.3 and 5.4. As indicated in Table 5.4, the final average installed fastener tension was 37.9 kips which is fairly close to the 39 kip minimum value. The snugging operation developed an average snug load in the fasteners of 17.1 kips. The interior fasteners of the connection exhibited large losses of preload during snugging with a mean value of 11.7 kips as reported in Table 5.3. The average loss in the exterior fasteners was about 1/2 of that amount at 5 kips. During the full swaging pass, the magnitudes of the average tensile load loss dropped in both the interior and exterior fasteners to 1.1 and 0.3 kips, respectively, Figures 5.40 through 5.42 show load histories for typical fasteners from the interior and exterior regions of the connection.

Test HDS-4:

Figures 5.43 to 5.47 and Tables 5.3 and 5.4 present the observed results of test HDS-4. From Table 5.4, the average final installed tension was 33.1 kips, well below the minimum specified value. Table 5.3 indicates that the average initial snug load was 13.4 kips. The preload losses during the snugging sequence were comparable to those of test HDS-3 with average values for the interior fasteners of 11.3 kips and 5.4 kips for the exterior fasteners. During the final swaging pass the average tension loss for the interior fasteners was 12 kips and the average loss for the exterior fasteners was 2.9 kips. Load histories for fasteners 4 and 8 (interior) and 2 (exterior) are shown in Figures 5.45 through 5.47.

Figures 5.48 through 5.50 show photographs of the test connection in the original (pre-test) condition, after the snugging pass, and after the final tightening pass (after touch-up). Note that the snug loads were unable to pull out all of the visible gap in the plates. Upon final tightening, however, all visible gap appeared to have been removed from the connection plates.

5.4 CONCLUSIONS OF THE HUCK FASTENER TESTS

Table 5.5 provides a summary of the tests conducted on the Huck International C50L fasteners. Test conditions as well as final average tensions are summarized. From the results of these tests the following conclusions may be derived:

1.) Single pass installation of the LC collars onto the C50L pins in nominally flat plates produces average fastener tensions near, or just above, the 39 kip minimum. This condition occurs for all three grip lengths as is shown in Table 5.1.

2.) Single pass installation (no snugging) of the Huck fasteners into connections with a deformed middle plate did not produce adequate fastener preloads, except for the 2" grip connection (see Table 5.2). For the 2" grip (test HDNS-2), the plates were apparently flexible enough to deform during the installation of individual fasteners and remove the initial plate gap. Little preload loss occurs in the fasteners of the connection and the splice behaves similarly to a flat plate connection. In the 3" and 4" grip connections, the stiffness of the plates of the

Test #	Average Initial Snug Fastener Tension	Standard Deviation	Average Snug Tension Loss in Interior Rows	Standard Deviation	Average Snug Tension Loss in Exterior Rows	Standard Deviation
HDS-2	11.2	1.8	4.3	1.8	1.1	1.2
HDS-3	17.1	1.6	11.7	2.2	5.0	2.6
HDS-4	13.4	1.6	11.3	2.3	5.4	3.7

Note: All values in Kips

Table 5.3: Summary of fastener load results for HDS series tests - snugging pass

Test #	Average Final "Tight" Fastener Tension	Standard Deviation	Average Final Tension Loss in Interior Rows	Standard Deviation	Average Final Tension Loss in Exterior Rows	Standard Deviation
HDS-2	34.6	1.5	2.7	0.6	1.2	0.3
HDS-3	37.9	1.5	1.1	0.9	0.3	0.2
HDS-4	33.1	6.9	12.0	2.2	2.9	1.7

Note: All values in Kips

Table 5.4: Summary of fastener load results for HDS series tests - tightening pass

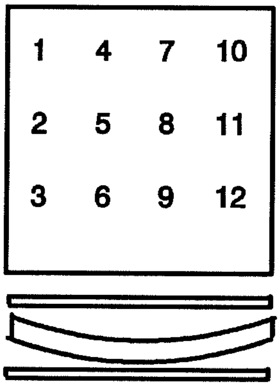
Fastener Number

		4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
Snugging Order	4.0	10.4	0	-0	0	-0	-0	0	0	-0	0	-0.1	-0.1
	5.0	5.9	11.9	-0	0	0	0	0.1	0.1	-0	0	-0	-0
	6.0	6.3	7.7	11.4	0	0	-0	0.1	0	0	0	-0	-0.1
	7.0	9.3	9.2	11.4	11.6	0	-0	0.1	0.1	0	0	-0	-0
	8.0	9.3	10.1	11.1	8.8	13.9	-0	0	0	-0	-0	-0	-0
	9.0	9.3	10.8	9.3	8.7	11.1	12.0	0	0	-0	-0	-0.1	-0
	1.0	4.0	7.5	8.3	8.8	10.8	11.8	11.6	0	-0	0	-0.1	-0.1
	2.0	4.4	6.2	6.7	8.8	10.7	12.0	9.1	8.4	-0	0	-0.1	-0
	3.0	4.3	6.4	6.2	8.7	10.7	12.1	9.0	6.0	14.5	-0	-0.1	-0.1
	10.0	4.5	6.3	6.4	6.0	10.0	11.7	9.0	6.0	14.2	9.7	-0	-0
	11.0	4.6	6.3	6.5	6.2	10.2	11.3	9.0	6.0	14.1	10.1	8.9	-0
	12.0	4.5	6.3	6.6	6.2	10.4	11.4	9.0	6.0	14.0	10.0	8.7	9.6
Tightening Order	4.0	38.1	5.3	5.4	5.7	9.4	10.3	8.1	5.1	12.3	8.6	7.3	8.3
	5.0	37.9	35.9	5.6	5.7	9.9	10.4	8.1	5.4	11.9	8.5	7.2	8.2
	6.0	37.1	34.9	37.3	5.0	9.3	8.4	7.3	4.6	11.6	7.7	6.4	7.0
	7.0	37.2	34.8	36.9	34.9	8.9	8.4	7.2	4.5	11.5	7.8	6.3	7.0
	8.0	37.1	34.9	36.8	34.4	39.7	8.3	7.1	4.4	11.4	7.7	6.4	6.8
	9.0	36.2	34.0	35.9	33.6	38.7	35.5	6.2	3.5	10.4	6.7	5.5	6.4
	1.0	36.1	33.9	35.9	33.4	38.5	35.1	36.4	3.5	10.2	6.6	5.4	6.3
	2.0	36.0	34.0	35.9	33.4	38.5	35.1	36.3	35.7	10.7	6.4	5.4	6.2
	3.0	35.5	33.4	35.5	32.9	38.0	34.6	35.7	35.2	38.3	5.9	4.9	5.7
	10.0	35.5	33.4	35.5	32.9	38.0	34.5	35.7	35.1	38.1	35.8	5.1	5.5
	11.0	35.1	32.9	35.1	32.5	37.6	34.1	35.2	34.7	37.6	35.2	36.2	5.5
	12.0	34.7	32.5	34.7	32.1	37.2	33.8	34.8	34.3	37.2	34.7	35.5	33.5

Tension in Kips

Average Fastener Tension = 34.6 Kips

28 Grip Huck C50L Fasteners
2" Grip
Deformed Plates
Two Pass Installation
(w/Snugging Pass)



Fastener Numbers

Figure 5.33: Fastener Tensions for Test HDS-2

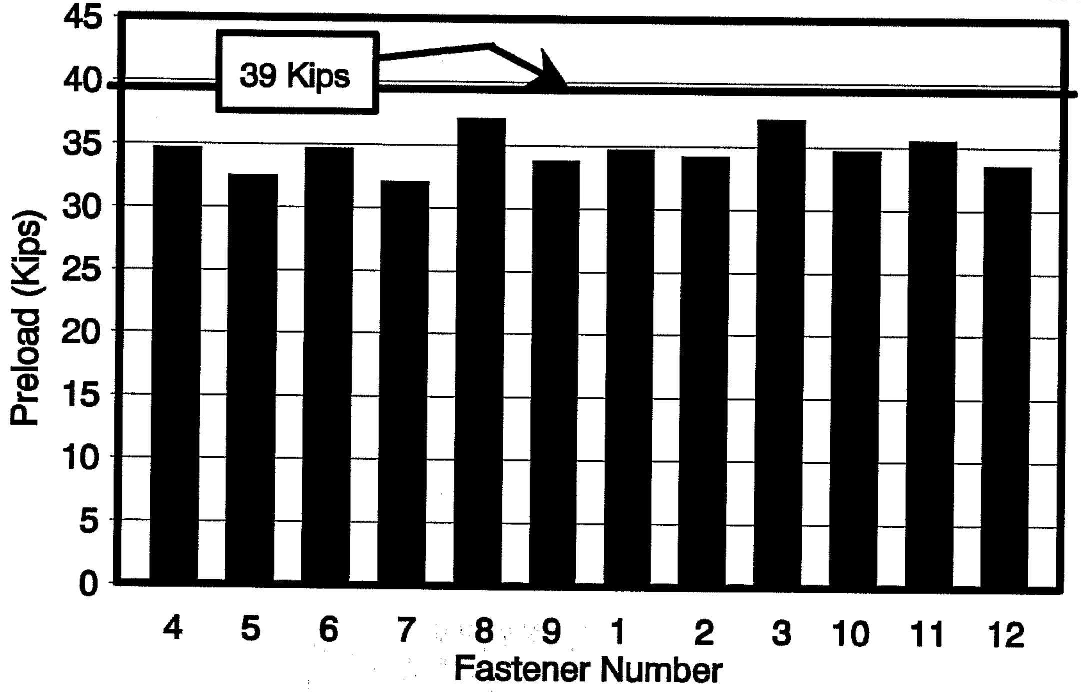


Figure 5.34: Final Installed Tensions for Test HDS-2

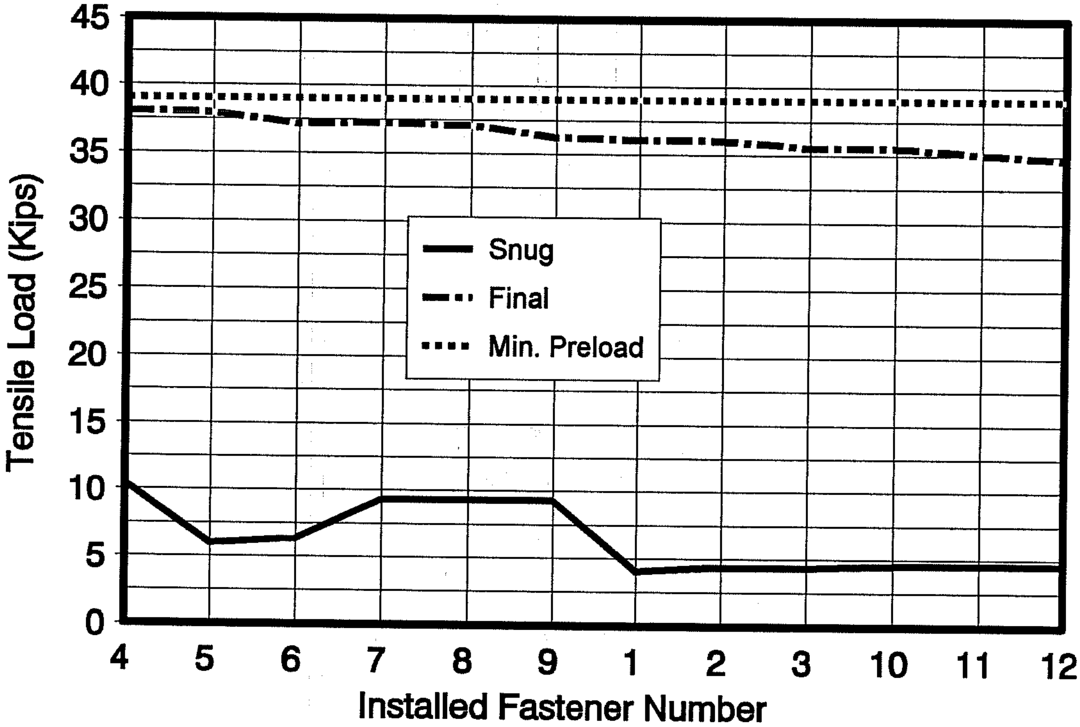


Figure 5.35: Tensile Load History for Fastener #4 - Test HDS-2

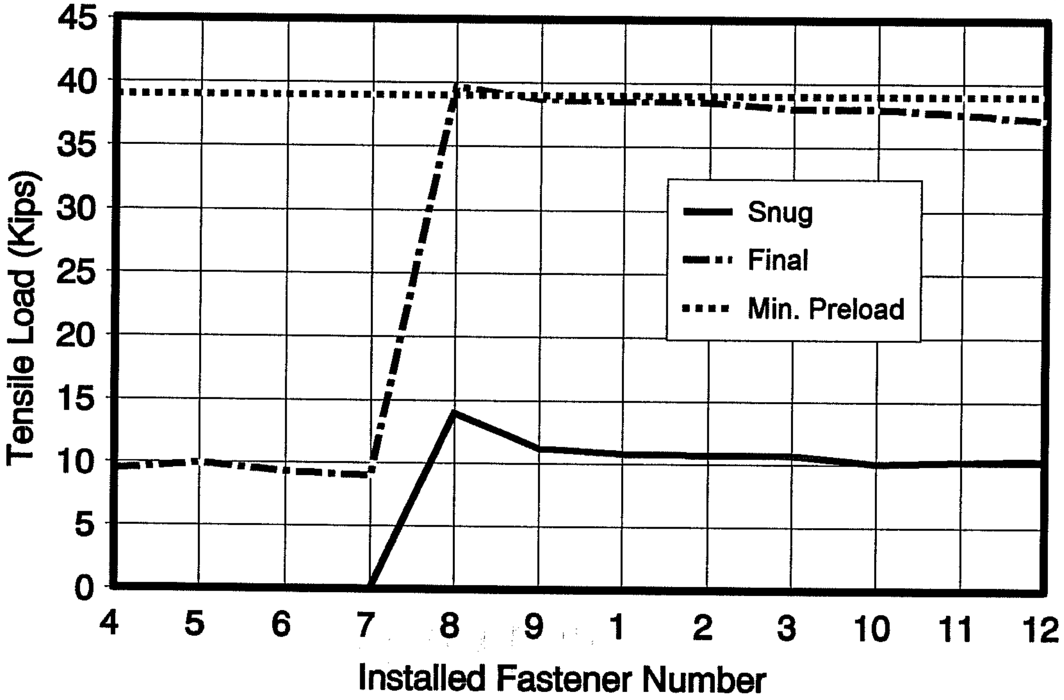


Figure 5.36: Tensile Load History for Fastener #8 - Test HDS-2

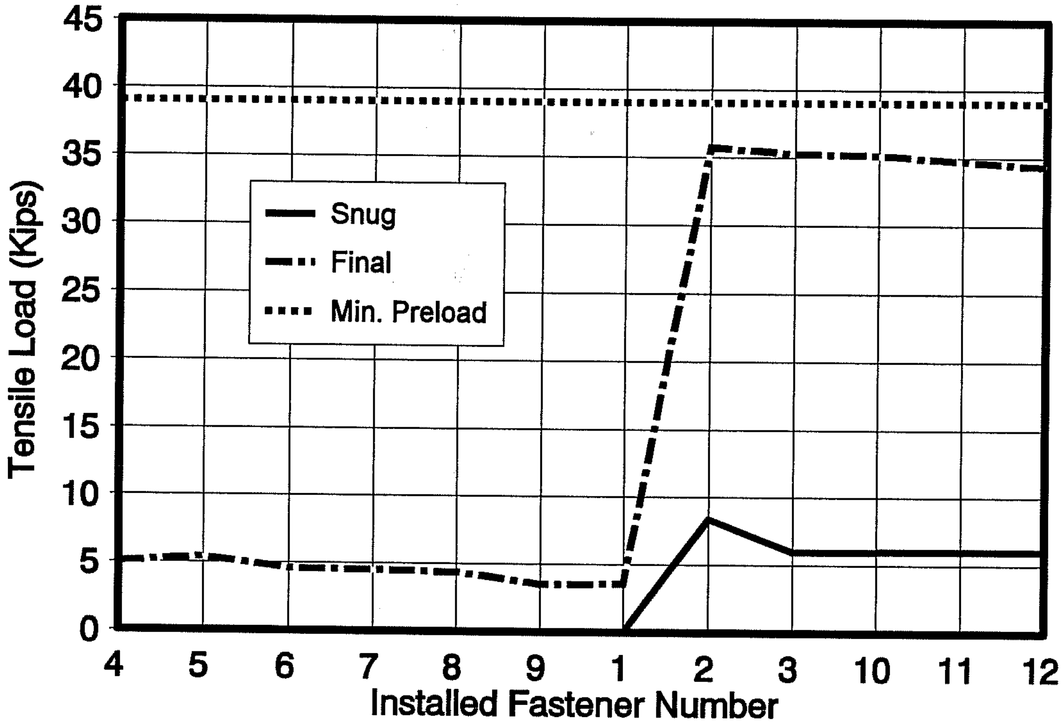


Figure 5.37: Tensile Load History for Fastener #2 - Test HDS-2

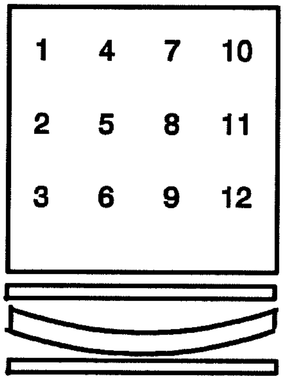
Fastener Number

		4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
Snugging Order	4.0	17.2	0.1	0.1	0.2	0.1	0.1	0.2	0	0.2	0.1	0.2	0.1
	5.0	7.1	18.6	0.1	0.1	0.1	0.1	0.1	0	0.2	0.1	0.1	0.1
	6.0	7.2	8.3	15.0	0.2	0.2	0.1	0.1	-0.1	0.3	0.1	0.2	0.1
	7.0	5.3	5.1	16.0	14.4	0.1	0.1	0.1	-0.1	0.3	0	0.2	0.1
	8.0	7.0	3.9	15.7	6.7	17.5	0.1	0.1	-0.1	0.2	0	0.1	0.1
	9.0	7.7	4.7	11.6	6.8	10.1	18.5	0.1	-0.1	0.1	-0	0.1	0.1
	1.0	1.7	2.9	7.7	10.0	12.4	19.3	19.4	-0	0.3	0.1	0.2	0.1
	2.0	1.9	2.5	5.5	9.9	13.0	19.6	13.6	16.3	0.1	0	0.1	0.1
	3.0	1.9	2.6	3.0	10.0	13.8	20.5	14.1	8.7	19.5	0	0.1	0.1
	10.0	3.0	3.5	3.6	4.8	7.7	17.5	13.9	8.6	18.9	16.6	0.1	0.1
	11.0	3.1	4.0	4.2	4.8	4.9	13.8	13.9	8.6	18.9	9.1	16.8	0.1
	12.0	3.1	4.1	4.4	4.9	4.9	9.6	13.9	8.5	19.3	9.7	12.2	15.8
Tightening Order	4.0	39.6	2.5	4.3	2.4	3.8	9.7	14.3	8.8	19.0	9.8	12.3	15.4
	5.0	39.0	40.9	3.4	2.4	2.5	8.6	14.5	9.0	19.1	9.8	12.4	18.2
	6.0	38.9	40.1	36.5	2.4	2.4	5.8	14.4	9.1	18.4	9.8	12.4	18.4
	7.0	37.7	40.0	36.1	39.9	1.9	5.8	14.4	9.1	18.4	9.0	12.2	20.0
	8.0	37.8	39.0	36.0	39.9	37.9	5.1	14.4	9.1	18.3	9.1	12.0	28.1
	9.0	37.8	39.2	34.3	39.8	37.7	37.6	14.4	9.1	18.5	9.2	12.2	20.9
	1.0	37.8	39.2	34.2	39.8	37.5	37.2	39.3	9.4	18.5	9.1	12.1	20.8
	2.0	37.9	39.3	34.2	39.7	37.5	37.1	39.5	37.2	19.0	9.1	12.1	22.6
	3.0	37.9	39.3	34.3	39.7	37.4	37.0	39.4	37.0	39.4	9.1	12.1	28.4
	10.0	37.9	39.3	34.3	39.8	37.5	37.0	39.4	36.8	39.1	39.4	12.0	28.6
	11.0	37.8	39.3	34.3	39.8	37.6	37.0	39.4	36.8	39.0	39.1	37.6	28.8
	12.0	37.8	39.2	34.3	39.8	37.7	37.2	39.4	36.7	38.9	38.9	37.4	B.G.

Tension in Kips

Average Fastener Tension = 37.9 Kips

44 Grip Huck C50L Fasteners
3" Grip
Deformed Plates
Two Pass Installation
(w/Snugging Pass)



Fastener Numbers

Figure 5.38: Fastener Tensions for Test HDS-3

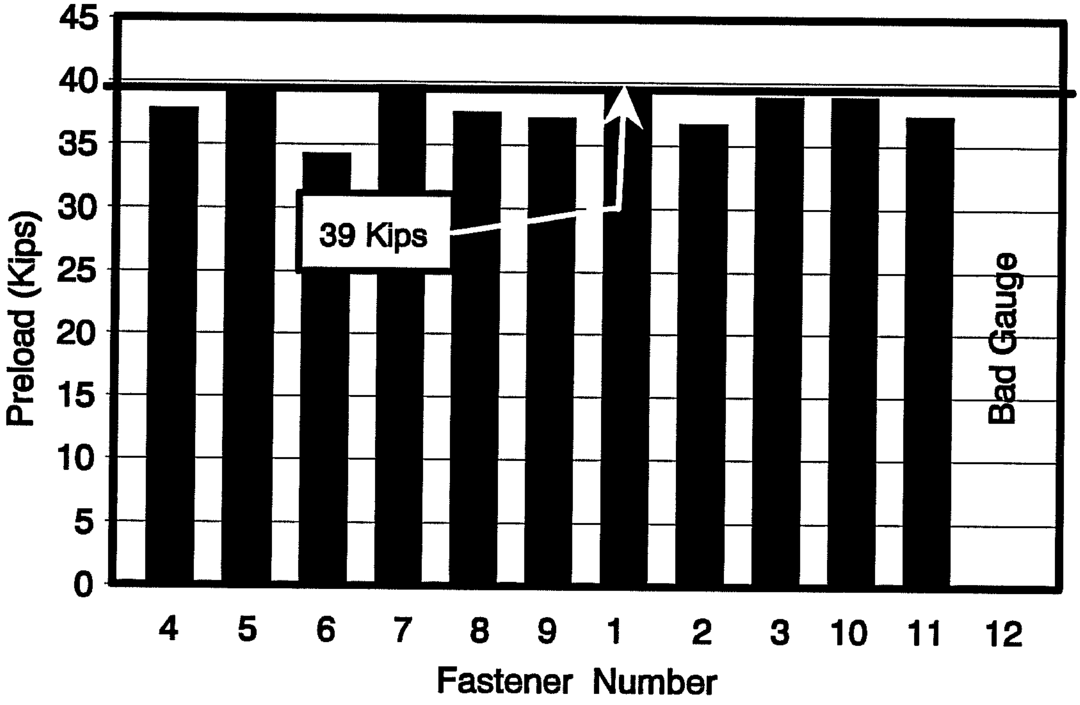


Figure 5.39: Final Installed Tensions for Test HDS-3

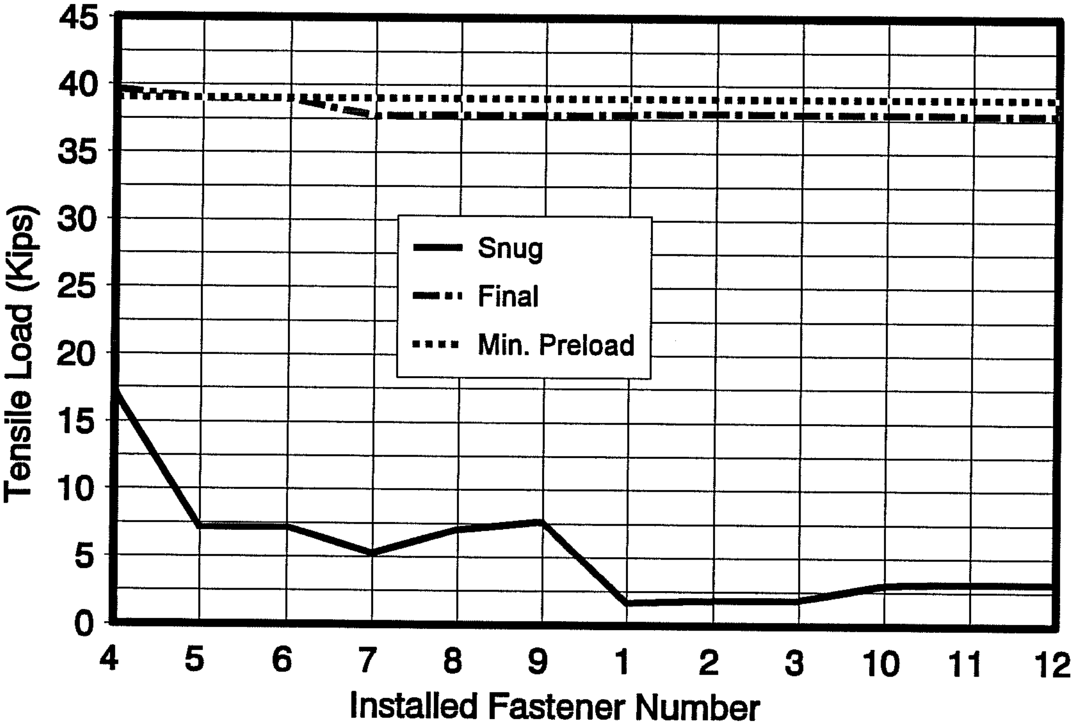


Figure 5.40: Tensile Load History for Fastener #4 - Test HDS-3

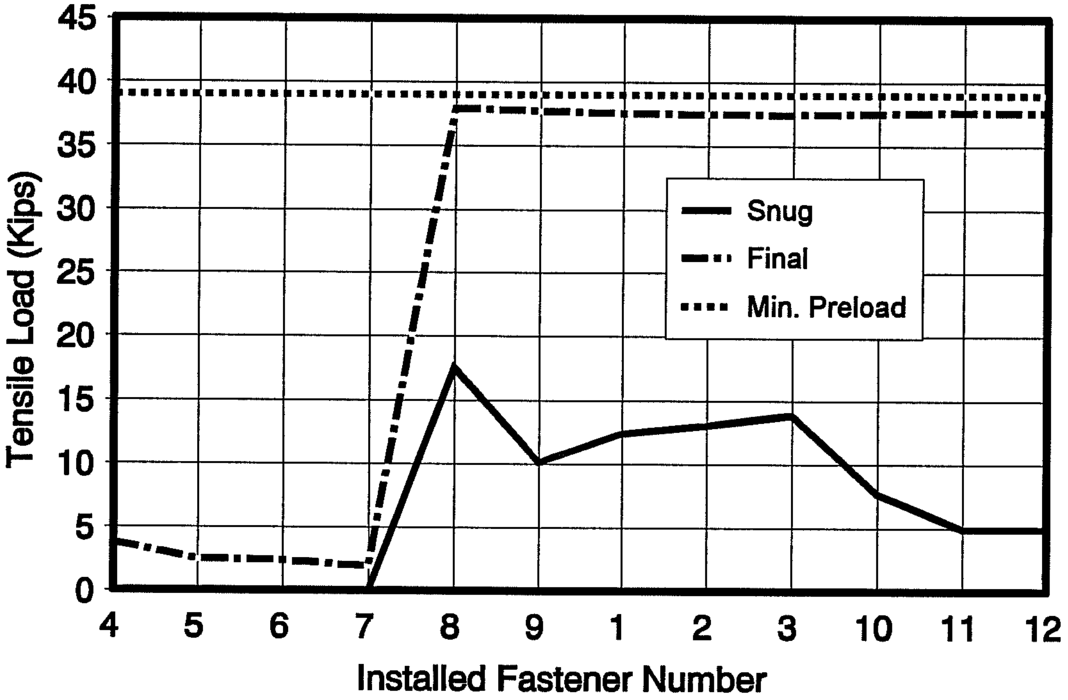


Figure 5.41: Tensile Load History for Fastener #8 - Test HDS-3

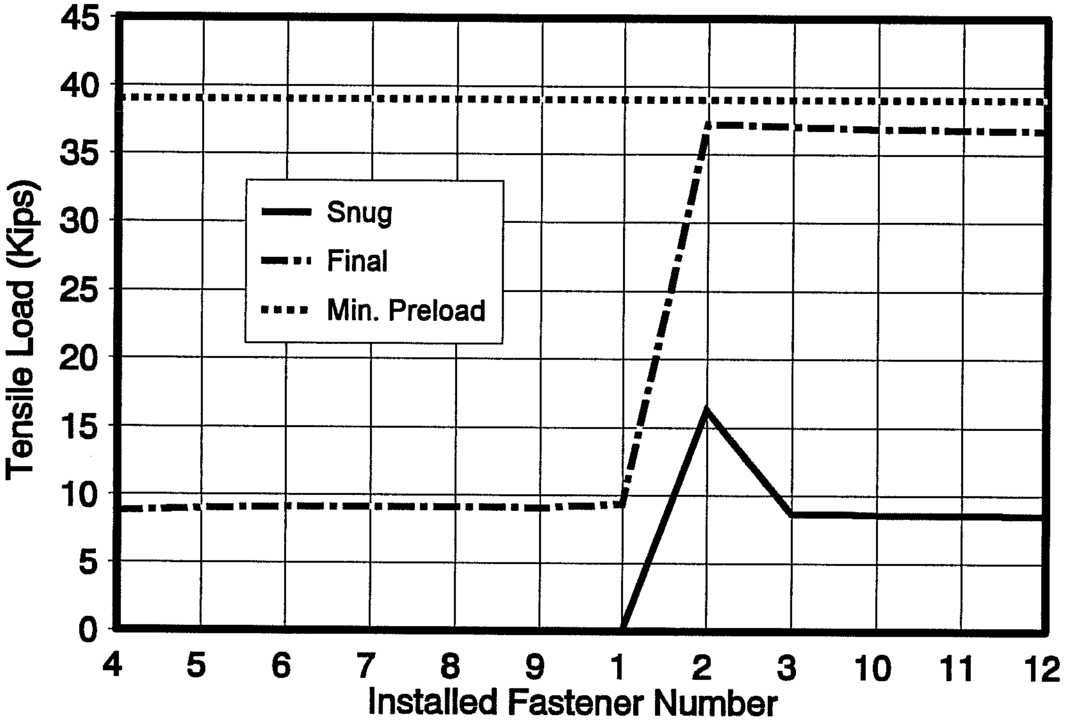


Figure 5.42: Tensile Load History for Fastener #2 - Test HDS-3

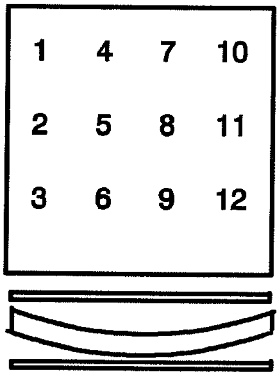
Fastener Number

		4.0	5.0	6.0	7.0	8.0	9.0	1.0	2.0	3.0	10.0	11.0	12.0
Snugging Order	4.0	13.1	0.1	0	0.0	0.1	0	0	0.0	0.1	-0.1	0.3	0.2
	5.0	7.0	10.6	-0.5	0	0.1	0.1	0.1	0	0.1	-0	0.3	0.4
	6.0	6.6	2.4	15.3	-0	-0	-0	-0	-0	0	-0.1	0.2	0.7
	7.0	2.0	1.2	14.4	13.7	0	-0	0	-0	0	-0	0.1	0.8
	8.0	2.8	0.8	11.4	6.9	11.0	-0	0	-0	0	-0.1	0.1	0.8
	9.0	4.1	1.3	7.2	6.3	3.9	12.0	0	-0	0	-0.1	0.1	0.8
	1.0	0.2	-0.1	1.6	8.0	7.6	12.3	13.0	-0	0	-0.1	0.4	0.9
	2.0	0.2	-0.1	-0.1	9.2	8.2	12.9	2.2	15.8	0	-0.1	0.4	0.9
	3.0	0.2	-0.1	-0.2	9.9	8.8	11.6	1.9	5.4	14.3	-0.1	0.3	0.9
	10.0	0.2	-0.1	-0.3	3.0	4.5	10.6	4.3	7.8	14.9	13.7	0.3	0.9
	11.0	0.2	-0.1	-0.3	3.6	1.9	7.1	4.8	9.0	15.3	6.8	13.6	0.9
	12.0	0.2	-0	-0.2	4.6	1.8	1.4	4.8	10.2	15.9	7.3	5.2	15.2
Tightening Order	4.0	38.1	-0.1	-0.1	-0.1	0.0	-0.1	0.1	4.8	15.3	6.9	5.9	15.3
	5.0	28.8	36.5	-0.1	-0.1	0.0	-0.1	0.1	3.0	10.7	7.4	5.5	13.9
	6.0	29.4	27.4	37.0	-0.1	0.0	-0.1	0.1	3.5	4.0	7.8	6.1	11.7
	7.0	26.7	26.6	36.3	41.6	0.0	-0.1	0.4	4.7	4.6	0.2	2.1	12.3
	8.0	28.0	25.7	35.2	35.4	41.5	-0.1	0.7	5.5	5.6	-0	0.4	7.3
	9.0	28.4	26.9	29.3	35.3	34.6	41.0	0.7	6.3	7.8	-0	0.4	29.3
	1.0	24.8	25.0	29.4	36.3	34.9	40.6	42.0	2.1	5.1	-0	0.4	33.3
	2.0	25.4	23.6	27.8	36.3	35.1	41.1	39.6	40.7	0.3	-0	0.4	34.3
	3.0	25.5	24.3	26.4	36.1	35.2	41.1	39.7	36.6	42.0	-0	0.3	44.6
	10.0	26.3	24.7	26.9	26.5	28.4	37.5	39.7	36.6	41.7	50.5	0.5	44.4
	11.0	26.4	24.8	27.3	27.1	25.9	33.2	39.7	36.6	41.6	45.1	40.1	44.4
	12.0	26.4	24.8	27.6	27.2	26.3	31.2	39.7	36.6	41.6	45.0	37.7	B.G.

Tension in Kips

Average Fastener Tension = 33.1 Kips

60 Grip Huck C50L Fasteners
4" Grip
Deformed Plates
Two Pass Installation
(w/Snugging Pass)



Fastener Numbers

Figure 5.43: Fastener Tensions for Test HDS-4

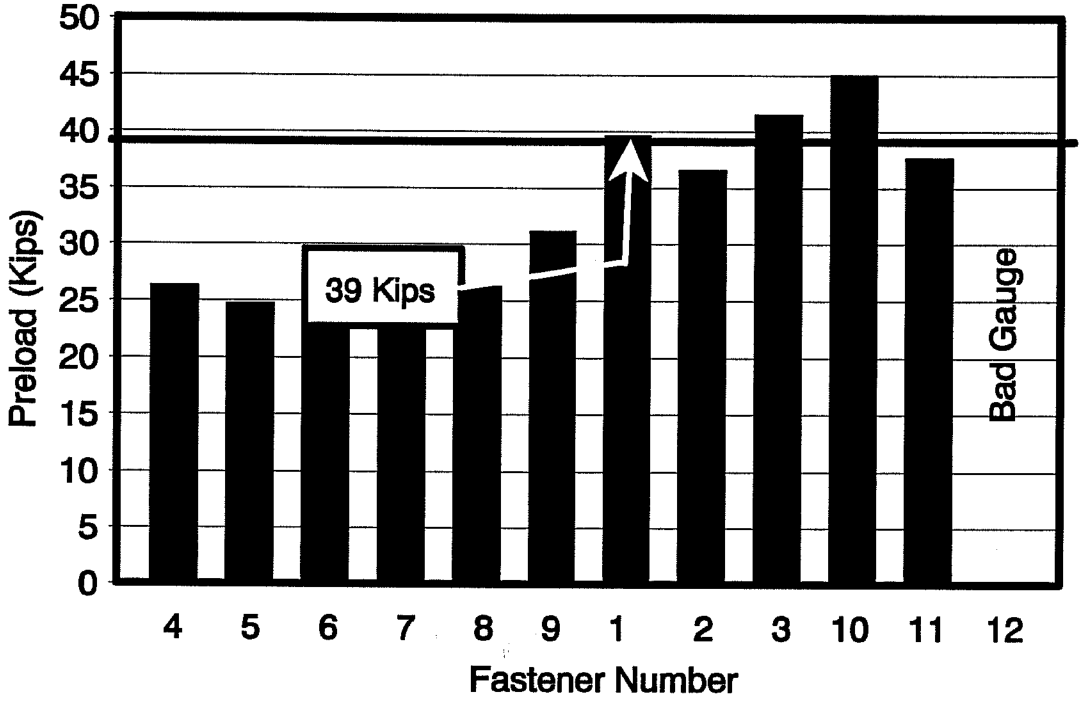


Figure 5.44: Final Installed Tensions for Test HDS-4

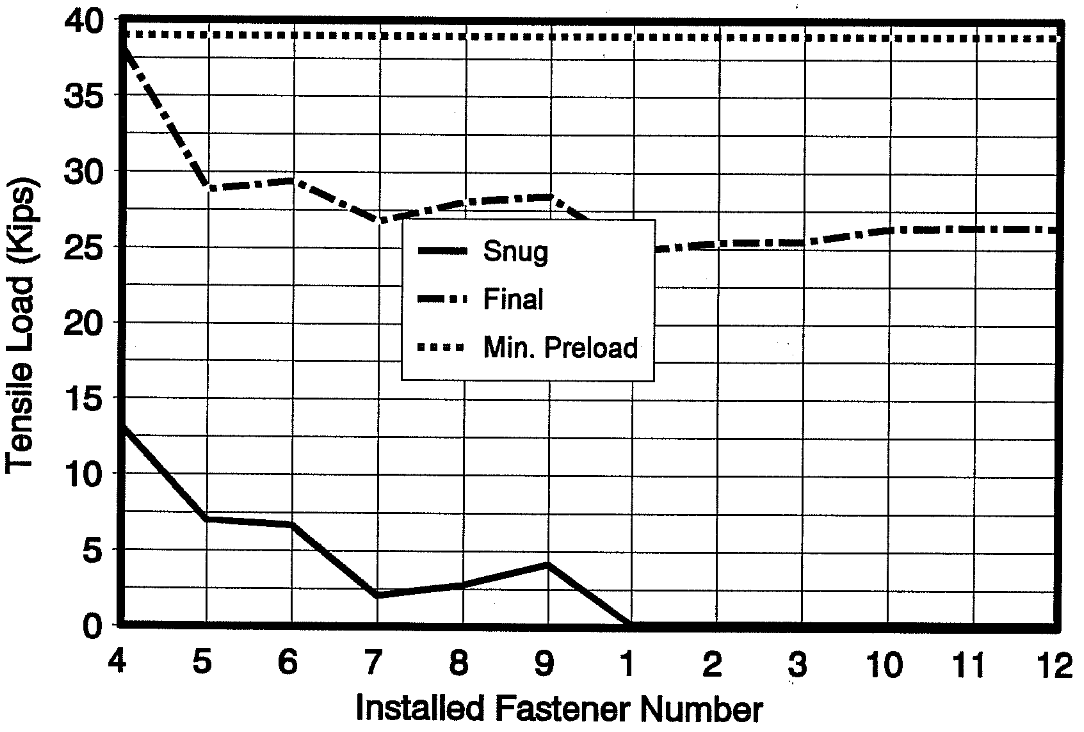


Figure 5.45: Tensile Load History for Fastener #4 - Test HDS-4

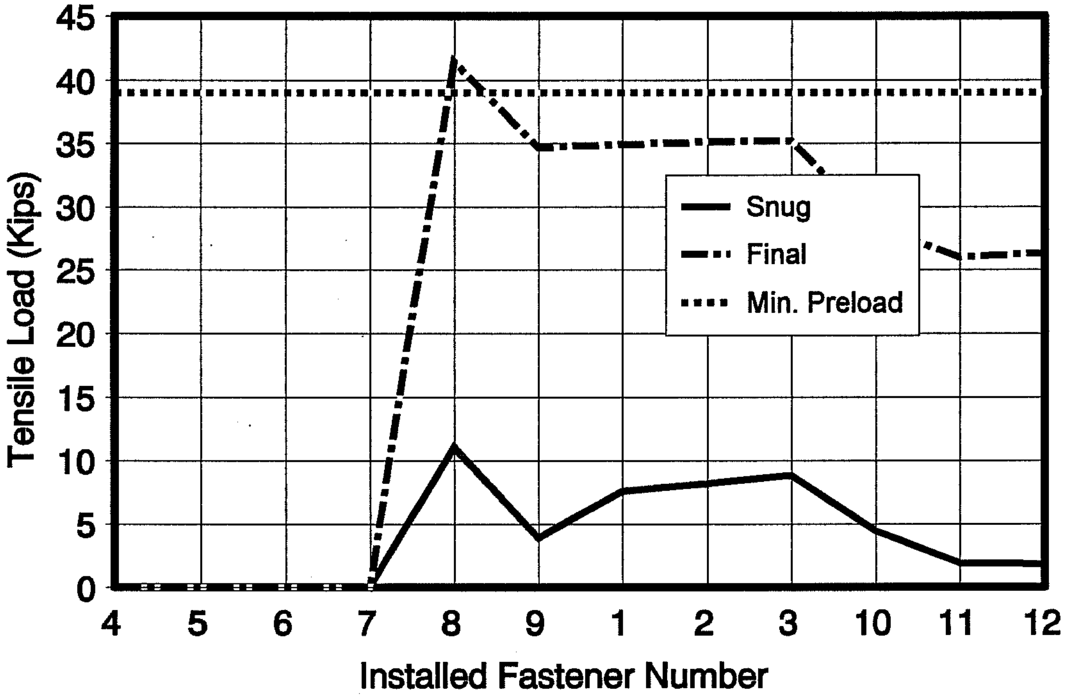


Figure 5.46: Tensile Load History for Fastener #8 - Test HDS-4

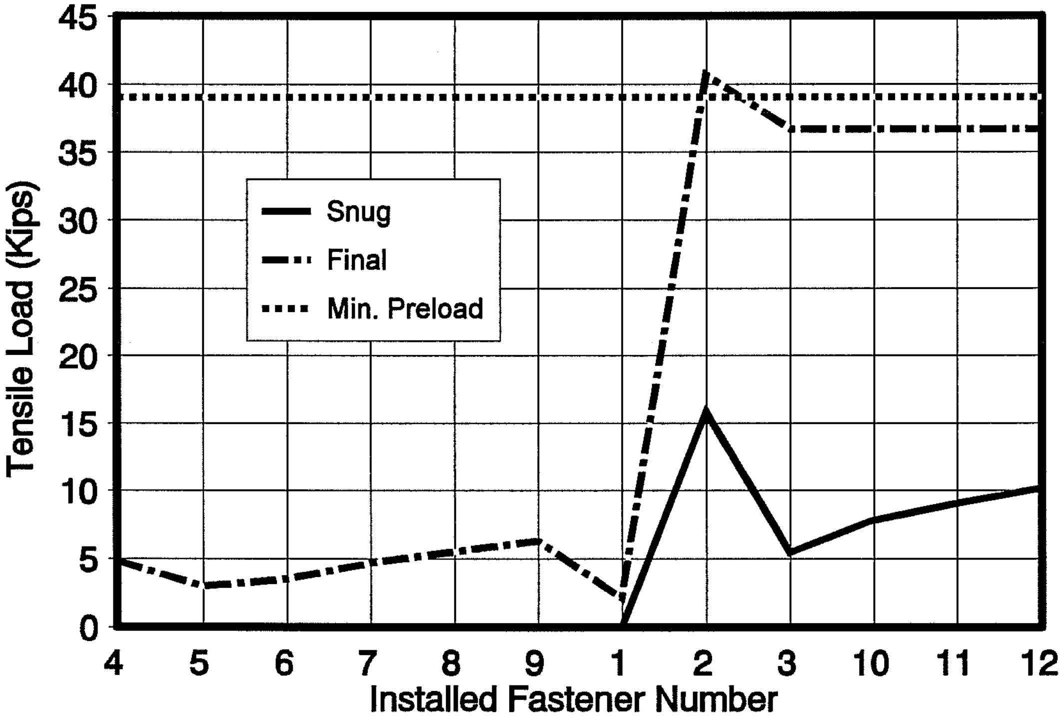


Figure 5.47: Tensile Load History for Fastener #2 - Test HDS-4

Figure 5.50: Connection plates for test HDS-4 in fully tightened condition

Test	Grip	Plate Conditions	Installation Method	Aver. Tension
HFNS-2	2"	Flat	Single Pass (no snug)	38.4
HFNS-3	3"	Flat	Single Pass (no snug)	39.3
HFNS-4	4"	Flat	Single Pass (no snug)	40.4
HDNS-2	2"	Middle Plate Δ=3mm	Single Pass (no snug)	38.9
HDNS-3	3"	Middle Plate Δ=3mm	Single Pass (no snug)	32.5
HDNS-4	4"	Middle Plate Δ=3mm	Single Pass (no snug)	31.5
HDS-2	2"	Middle Plate Δ=3mm	Two Pass (w/snugging)	34.6
HDS-3	3"	Middle Plate Δ=3mm	Two Pass (w/snugging)	37.9
HDS-4	4"	Middle Plate Δ=3mm	Two Pass (w/snugging)	33.1

Note: All values in Kips

Table 5.5: Summary of Huck fastener connection tests

connection appears to prevent individual fasteners from removing enough of the gap in the connection plies to prohibit subsequent fastener tensile loss. Table 5.2 shows that the average final fastener tensions become smaller and the average fastener preload loss becomes greater with increasing grip (and plate) thickness. A single pass installation of the C50L lock-pins and LC collars does not result in an adequately fastened joint for lap splices with thicker, deformed plates.

3.) Snugging during the installation of the Huck fasteners (HDS series tests) showed mixed results as to the effect of the procedure on final fastener tensions. During test HDS-2 (2" grip), snugging reduced the average final fastener preload as compared to the results given by single pass installation with no snugging (HDNS-2). During the 3" grip test with a deformed middle plate, the snugging pass produced a 5 kip gain in the final installed fastener tensions as compared to the 3" grip test with no snugging (HDNS-3). For the 4" grip test, the average fastener tension increase was only 1.6 kips between tests HDNS-4 (no snugging) and HDS-4 (with snugging).

Best results for the HDS series tests were obtained for the 3" grip (HDS-3). As indicated in Table 5.3, the average initial snug load for test HDS-3 was 17.1 kips, versus 11.2 kips and 13.4 kips for tests HDS-2 and HDS-4, respectively. This higher initial snug load on test HDS-3 may have been responsible for the higher final installed fastener tensions. The lower snug loads in tests HDS-2 and HDS-4 may have left substantial gap between the plates. In the final full swage tightening pass, the limited elongation available in the Huck fastener after initial collar swage (i.e. after snugging) may have been insufficient to compress the remaining gap.

CHAPTER 6

OVERALL SUMMARY AND CONCLUSIONS

Tables 6.1 through 6.4 provide a summaries of the various installed fastener tension results for each test conducted. Table 6.1 shows the results for the flat plate tests while Tables 6.2 to 6.4 summarize those for connections with a deformed middle plate. Based on these tables, the following conclusions can be derived:

1.) For the connections made up of nominally flat plates, the average final installed tensions in both the conventional A325 and Huck fasteners were very close to, or exceeded, the 39 kip minimum value mandated by the *Bolt Specification* . The Huck fasteners installed with one pass exhibited an average tension which was very comparable to that observed in conventional A325's installed with a calibrated wrench using no snugging. As expected, the turn-of-nut installation procedure for conventional A325 fasteners produced average preloads well in excess of the 39 kip minimum required value.

2.) For the connections which included a deformed middle plate, the only combination of fastener and installation method which produced consistently acceptable results was the turn-of-nut method applied to conventional A325 fasteners. For all three grip lengths tested, the turn-of-nut method (as described in Section 4.2.2) produced average final tensile loads in the fasteners that well exceeded the 39 kip minimum. For all tests except the 4" grip, the average final fastener preloads surpassed 50 kips.

It is important to note, however, that the snug loads used in the turn-of-nut installations were significantly higher than those used for the calibrated wrench installations or the Huck fastener tests (see Tables 6.2, 6.3, and 6.4). Consequently, a direct comparison between the turn-of-nut tests and the calibrated wrench or Huck fastener tests is not appropriate. Additional turn-of-nut tests with lower snugging loads would be desirable.

3.) For the 2" grip deformed plate tests, the Huck fasteners installed in two passes (test HDS-2) failed to achieve adequate fastener tensile loads. All other fasteners and methods of installation produced average final fastener preloads near, or above, 39 kips.

4.) In the thicker connection grips (3" and 4") with deformed middle plates, all fasteners and installation methods (except conventional A325 fasteners installed by turn-of-nut) failed to achieve adequate fastener tensions. The Huck fasteners installed with both single and double passes (with and without snugging) failed to exhibit 39 kips of average fastener preload for either grip length. Conventional A325 fasteners installed by the calibrated wrench method (again,with and without snugging) also lacked adequate average fastener tensions after the final installation pass. Tables 6.2 to 6.4 show that for both one and two pass installation, the Huck fasteners consistently exhibit higher final average preloads than the conventional A325 fasteners installed by calibrated wrench. With the application of additional touch-up passes (as mandated by the *Bolt Specification*), however, the tensions in the conventional A325 fasteners increase.

5.) As noted in the literature search summary in Section 1.3, field installation of conventiona A325 fasteners often differs substantially from the methods mandated by the *Bolt Specification* . While not exact, the methods used during this program of study for conventional A325 fastener installation were, for the most part, in accordance with the *Bolt Specification* guidelines. Thus, the results herein reported for the conventional A325 fastener tests may not be representative of those that would be found in the lap splice connections of actual structures.

The installation of Huck fasteners, conversely, provides very little room for deviation between actual field installation practice and the methods employed in the laboratory. The only variable is the utilization of a snugging pass and tests were conducted both with and without snugging of the Huck fasteners. Hence, the results contained in this report for Huck fastener installation tensions provide a good indication of the installed tensions of Huck C50L fasteners in actual structural applications.

Accordingly, to compare the results of the two fastener types, with regard to field installed performance, may be unfair and unrealistic. What should be considered is the individual performance of each type of fastener in the joints tested and the ability or inability of different installation methods to produce adequate fastener preloads.

Grip	Huck One Pass	Calibrated Wrench One Pass	Turn-of-Nut
2"	38.4	39.3	54.5
3"	39.3	40.9	51.7
4"	40.4	42.0	55.0

Note: All values in Kips

Table 6.1: Flat plate tests - Summary of average final installed fastener tensions

Installation Method	Average Initial Snug Tension	Average Final Snug Tension	Average Initial "Tight' Tension	Average Final "Tight"Tension
Calibrated Wrench (no snugging)	N/A	N/A	41.0	39.8
Calibrated Wrench (w/snugging)	11.0	7.8	40.1	39.5
Turn-of-nut	35.0	34.6	N/A	51.5
Huck C50L (no snugging)	N/A	N/A	39.2	38.9
Huck C50L (w/snugging)	11.2	8.6	36.4	34.6

Note: All values in Kips

Table 6.2: Summary of fastener tensions - 2" grip 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
Calibrated Wrench (no snug)	N/A	N/A	36.4	31.8	36.3	36.1
Calibrated Wrench (w/snug)	9.5	3.8	37.2	35.4	N/A	N/A
Turn-of-nut	30.0	26.5	N/A	50.9	N/A	N/A
Huck C50L (no snug)	N/A	N/A	39.6	32.5	N/A	N/A
Huck C50L (w/snug)	17.1	9.2	38.7	37.9	N/A	N/A

Note: All values in Kips

Table 6.3: Summary of fastener tensions - 3" grip 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
Calibrated Wrench (no snug)	N/A	N/A	40.0	27.3	38.7	38.0
Calibrated Wrench (w/snug)	10.7	4.3	40.5	30.4	39.2	38.8
Turn-of-nut	32.3	25.2	N/A	49.7	N/A	N/A
Huck C50L (no snug)	N/A	N/A	42.5	31.5	N/A	N/A
Huck C50L (w/snug)	13.4	5.3	41.0	33.1	N/A	N/A

Note: All values in Kips

Table 6.4: Summary of fastener tensions - 4" grip deformed plate tests

APPENDIX A
VERIFICATION TESTS

Upon receipt of the galvanized conventional A325 fasteners and the Huck International C50L lock pins (those to be used in the connection tests described in Chapters 4 and 5), several verification tests were performed to check the compliance of these fasteners with ASTM A325 specifications. Additionally, the conventional fasteners were tested for compliance with FHWA supplemental rotational capacity requirements and the Huck fasteners were tested to verify their ability to develop the installed tensions (clamp loads) required by the RCSC. The following tests were performed on the indicated fastener types:

ASTM A325 verification:

Direct tension: Conventional A325, Huck C50L
Rockwell hardness: Conventional A325, Huck C50L

FHWA "Supplemental Contract Specification" verification:

Rotational capacity: Conventional A325

RCSC Minimum Installation Tension verification:

Clamp Load: Huck C50L

The procedures and results of these tests are as follows:

Direct Tension Tests:

One conventional A325 fastener of each length (3-1/4", 4-1/4", and 5-1/4") was installed in the Huck tensioning jig (see Figure 3.3) and loaded in the Satec 600 kip testing machine. A linear potentiometer was used to measure displacement of the machine deck. Load was read directly from the test machine. All readings were taken and stored by the digital data acquisition system (see Section 3.4). The fasteners were loaded to fracture using a very slow strain rate. Figures A.1 to A.3 present typical load vs. deflection curves for all three lengths of fasteners. All fasteners tested exhibited ultimate loads in excess of the 55.45 kips specified by ASTM A325.

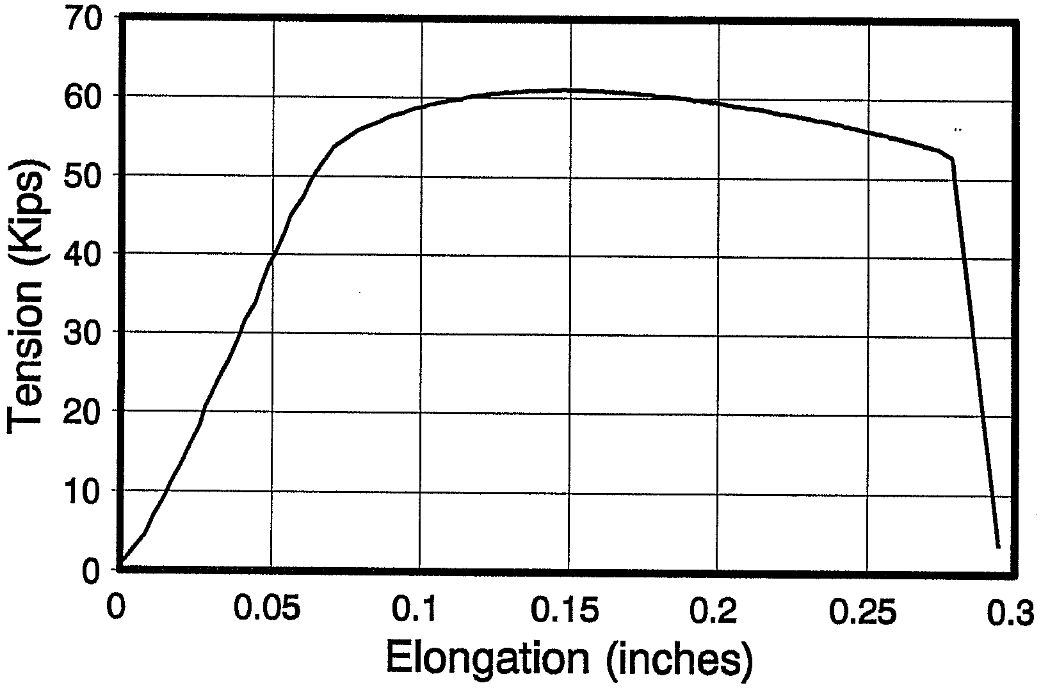


Figure A.1: Tension vs. elongation for 3-1/4" conventional A325

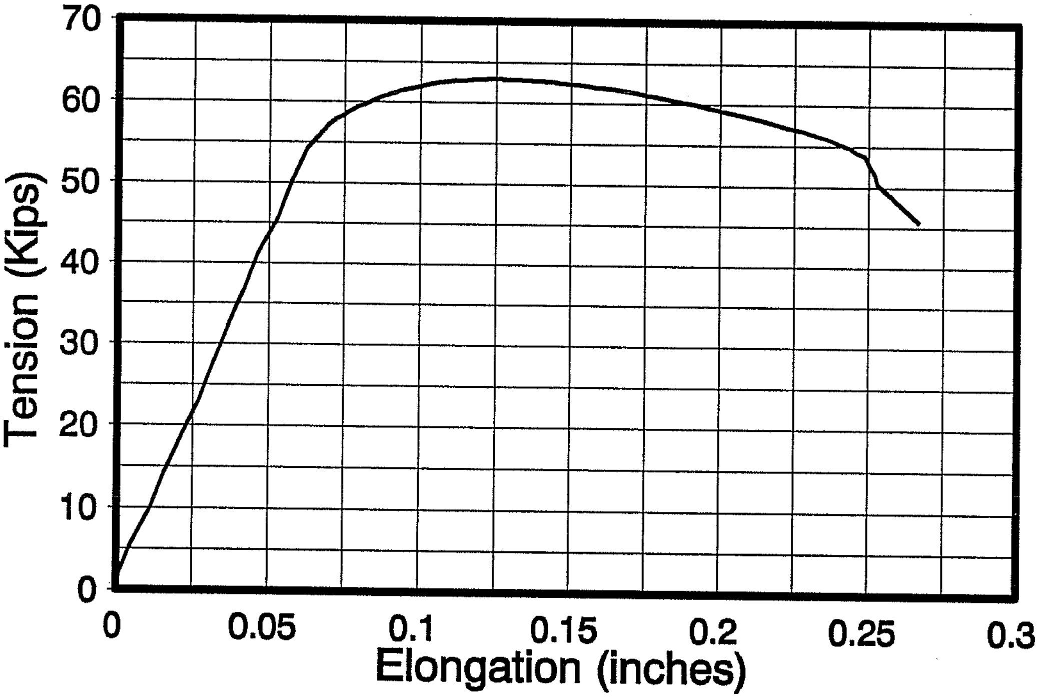


Figure A.2: Tension vs. elongation for 4-1/4" conventional A325

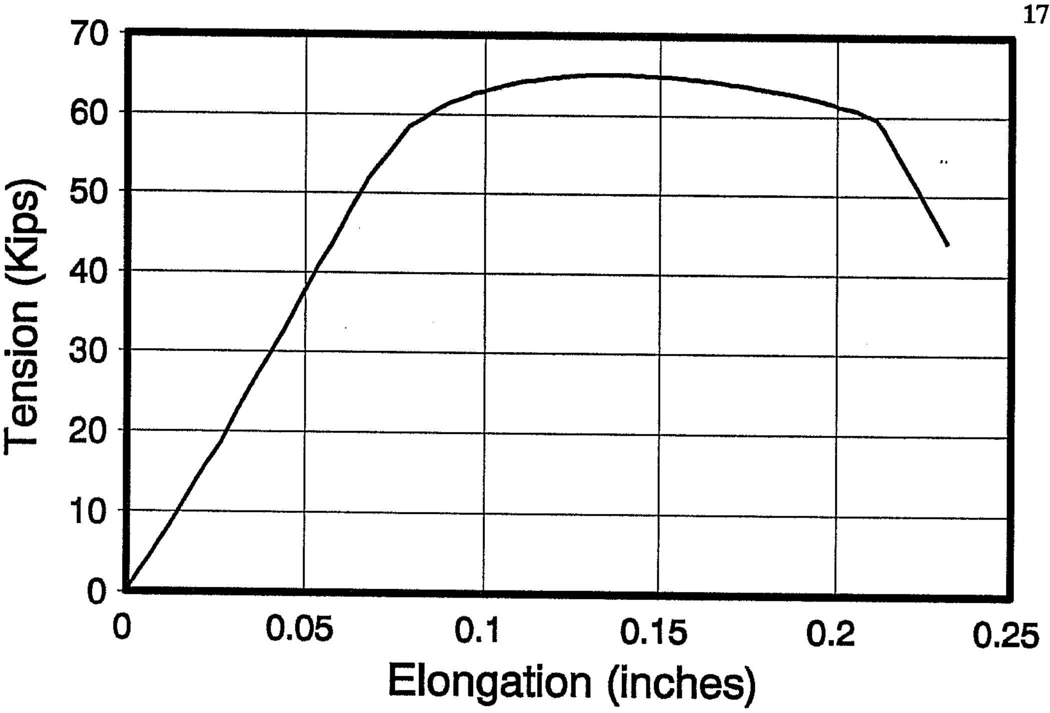


Figure A.3: Tension vs. elongation for 5-1/4" conventional A325

Fastener Tested	Ultimate Load (Kips)
28 Grip fastener	55.6
44 Grip fastener	53.3
60 Grip fastener	55.2

Note: All fasteners installed with LC collars

Table A.1: Summary of Huck fastener direct tension tests

One Huck fastener in each of the 28, 44, and 60 grip lengths was also tested. The Huck fasteners were installed in the plates of the Huck tensioning jig (see Section 3.3) with LC collars. They were then loaded in the 600 kip testing machine at a moderate strain rate until each fastener failed. For each fastener tested, failure occurred by stripping of the collar off of the pin. The ultimate loads recorded in Table A.1 show the largest values of tension recorded in each fastener, as indicated by the load dial on the 600 kip test machine. All fasteners tested either exceeded the ASTM A325 minimum ultimate load requirement of 55.45 kips or were very close (within about 3.5%) to this value.

Rockwell Hardness tests:

All Rockwell hardness tests were performed on a Wilson/Rockwell Series 500 hardness tester. These tests were performed on both the conventional A325 and Huck C50L fasteners. Cutting and machining of all specimens was conducted in the machine shop at the Phil M. Ferguson Laboratory. The locations of the tests for the different fasteners are as listed below:

Conventional A325 bolts (1 of each length):
    Wrench flats: 9 points on two faces
    Cross-section: 7 points on wafer cut 7/8" from end opposite the head
A563 grade DH nuts:
    Wrench flats: 9 points on two faces
    Nut bearing face: 10 points
    Cross-section: 10 readings
Huck C50L fasteners (1 of each grip length):
    Cross-section: 7 points on wafer cut 7/8" from break-neck on fastener body

The ASTM required Rockwell C hardnesses for 7/8" diameter A325 fasteners are a minimum of 24 and a maximum of 35. The Rockwell C range for the A563 nuts is 24 to 38. All hardnesses recorded in these tests fell with in the range of 29-32 and thus all samples met their respective Rockwell hardness requirements.

Rotational Capacity Tests:

These tests were performed on three conventional A325 fasteners of each length. The test procedure was a modification of an FHWA supplemental test for high-strength bolts in bridge applications. Tables A.2 and A.3 present the results of these tests. Figures A.4 through A.6 present typical torque vs. tension relationships for each length of fastener.

The tests were conducted by applying known values of torque to conventional fasteners installed in the Skidmore-Wilhelm bolt tension indicator. Fastener tension was read directly from the dial gauge on the Skidmore. After tightening the fasteners to an initial snug tension of about 5 kips, the torque wrench was set for increasing values of torque cut-off and readings of fastener tension were taken for these torque values. The initial position of the nut relative to the face plate of the Skidmore was also marked so that measured rotations past the initial snug tension could be made.

The adequacy of the thread lubrication was also checked in these rotational capacity tests. A theoretical value of torque was computed by multiplying a nut factor of 0.25 by the actual tension produced by the torque inducing a minimum of 39 kips of tension in the fasteners. This value was then multiplied by the diameter of the bolts in feet. This generated torque value had to be greater than or equal to the torque required to develop a minimum of 39 kips of tension in the fastener. These torque values which develop the minimum 39 kips of tension are listed in Tables A.2 and A.3, along with the computed values of torque to check the thread lubrication.

All fasteners tested exhibited the ability to withstand large nut rotations past snug conditions without thread stripping. As noted in Tables A.2 and A.3, the nuts were rotated as much as 1-1/4 turns past snug tight (4-1/4" and 5-1/4" fasteners). Loosening of the nuts and removal of the fastener assemblies from the Skidmore was accomplished easily with no signs of thread stripping. A visual check of the tested fasteners also showed no apparent stripping of the threads. The fasteners of each length developed the required minimum of 45 kips of tension at the appropriate nut rotation past initial snug tight (either 2/3 or 1 turn). All fasteners met the thread lubrication and rotational capacity requirements of the FHWA specifications.

Huck Fastener Clamp Load Tests:

Three Huck fasteners from each of the 28, 44, and 60 grip lengths were installed in the Skidmore-Wilhelm bolt tension indicator with LC collars. The tension in each fastener was read off of the load indicating dial gauge of the Skidmore. Table A.4 presents the results of these tests. As is shown, all of the fasteners installed in the Skidmore with tensions that exceeded the 39 kip minimum requirement for a 7/8" diameter A325 fastener. The *Bolt Specification*, however, requires that a fastener demonstrate the ability to develop 41 kips (39 kips + 5%) by a given

Fastener	Torque at min. 39 kips of Tension (ft.*#'s)	Tension at 2/3 turn past initial snug tight	Thread lubrcation torque check (ft.*#'s)	Tension at 1-1/12 turns past initial snug tight
3-1/4" #1	250	45 kips min.	712.8 > 250	50.6 kips
3-1/4" #2	260	45 kips min.	706.6 > 260	55.0 kips
3-1/4" #3	263	45 kips min.	696.0 > 263	55.7 kips

Table A.2: Summary of rotational capacity test results - 3-1/4" conventional A325 fasteners

Fastener	Torque at min. 39 kips of Tension (ft.*#'s)	Tension at 1 turn past initial snug tight	Thread lubrication torque check (ft.*#'s)	Tension at 1-1/4 turns past initial snug tight
4-1/4" #1	276	45 kip min.	711.0 > 276	55.5 kips
4-1/4" #2	250	45 kip min.	714.0 > 250	57.4 kips
4-1/4" #3	286	45 kip min.	711.0 > 286	58.0 kips
5-1/4" #1	250	45 kip min.	710.0 > 250	59.2 kips
5-1/4" #2	270	45 kip min.	711.0 > 270	58.9 kips
5-1/4" #3	250	45 kip min.	722.0 > 250	58.7 kips

Table A.3: Summary of rotational capacity test results - 4-1/4" and 5-1/4" conventional A325 fasteners

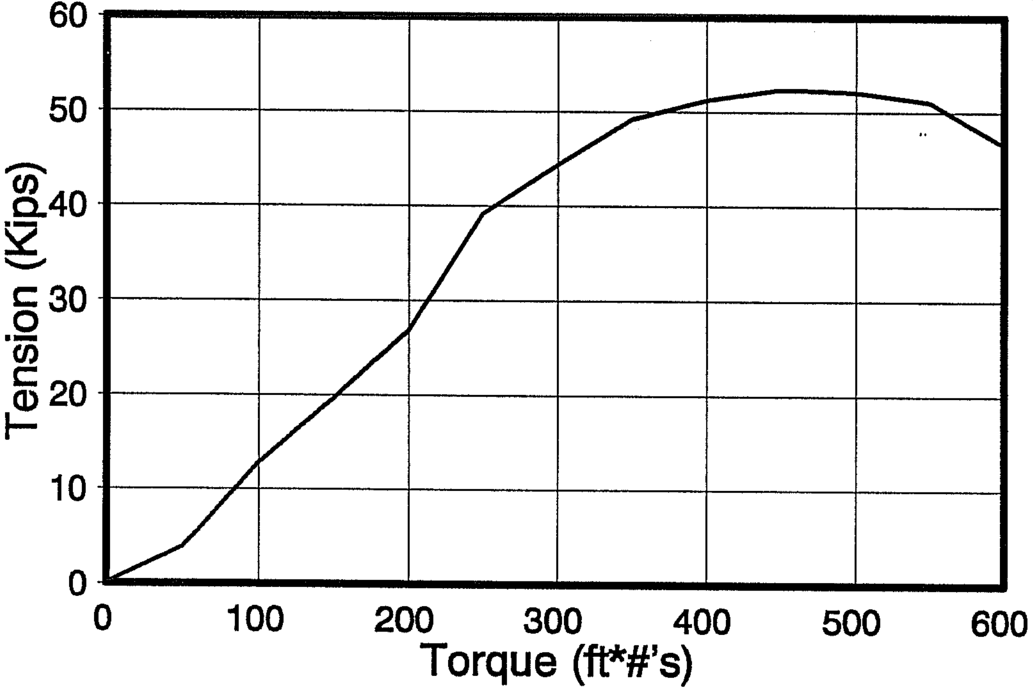


Figure A.4: Torque vs. tension for 3-1/4" conventional A325

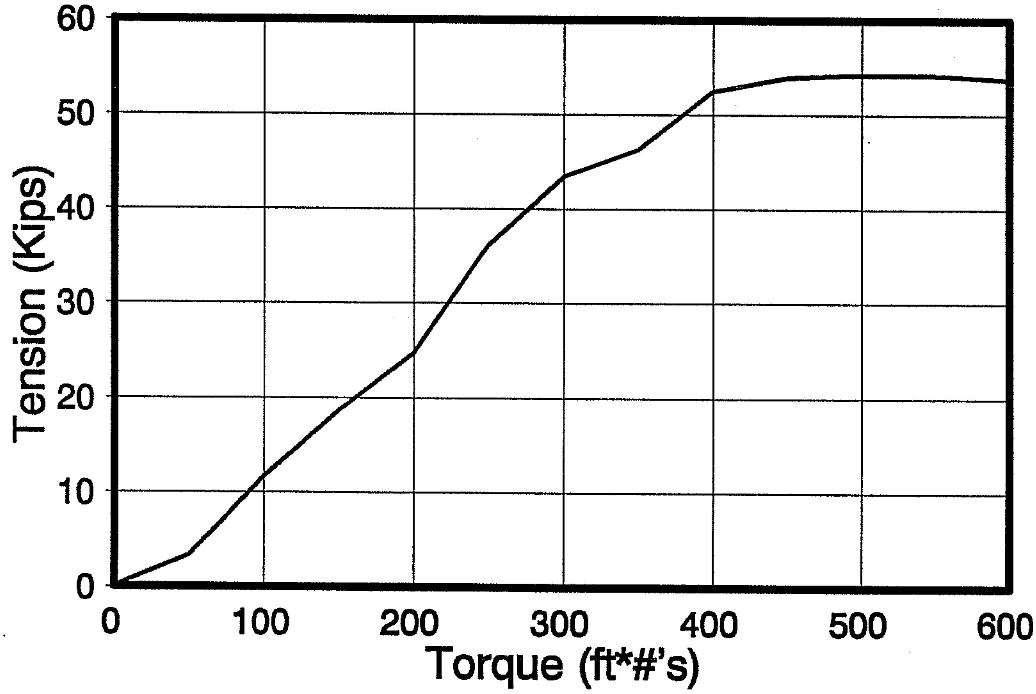


Figure A.5: Torque vs. tension for 4-1/4" conventional A325

Fastener Tested	Clamp Load (Kips)
28 Grip fastener #1	42.0
28 Grip fastener #2	41.0
28 Grip fastener #3	40.8
44 Grip fastener #1	41.0
44 Grip fastener #2	41.5
44 Grip fastener #3	40.0
60 Grip fastener #1	42.5
60 Grip fastener #2	41.5
60 Grip fastener #3	43.0

Note: All fasteners installed with LC collars

Table A.4: Summary of Huck fastener clamp load tests

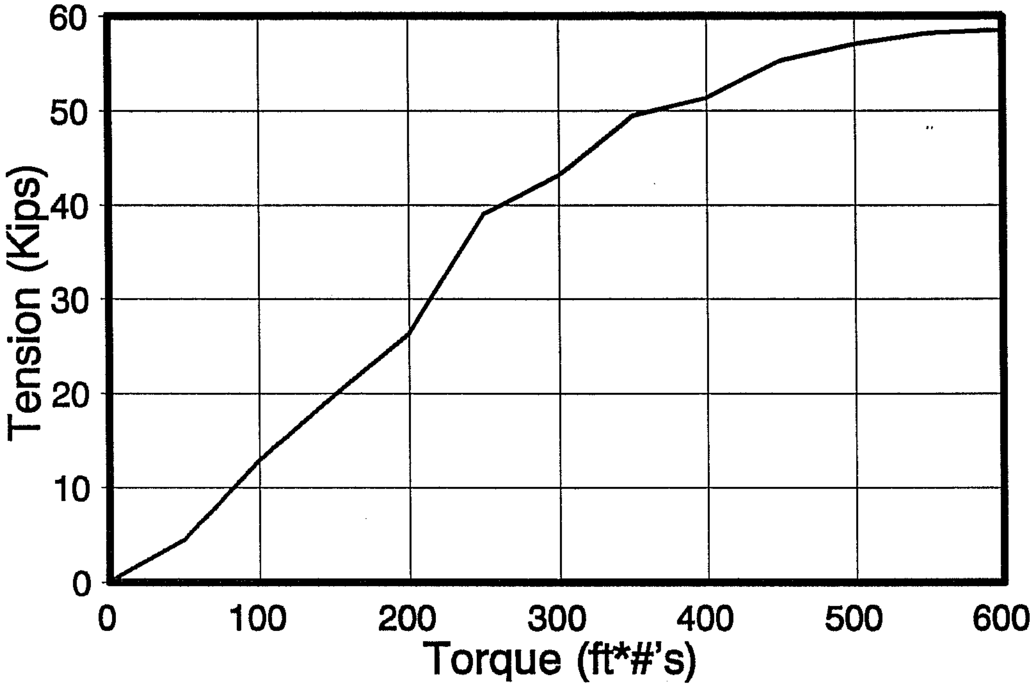


Figure A.6: Torque vs. tension for 5-1/4" conventional A325

installation method before actual field installation of that fastener can begin. One fastener (32 grip #2) failed to meet this requirement.

APPENDIX B

PLATE OUT-OF-FLATNESS MEASUREMENTS

Upon receipt of the connection plates from the local fabricator, measurements were taken to determine the relative "flatness" of each plate. Individual plates were first inscribed with a 12"x12" grid of 1" squares on one face. This was designated the upper face for each plate so that all subsequent tests could be performed with the plates in the same orientation.

The scribed plates were then clamped to the horizontal deck of a Lagun Republic model FTV-2S vertical milling machine. The plates were fastened to the deck with as little clamping force as possible to avoid deformation of the plates. A linear potentiometer was mounted in the spindle of the milling machine and was connected to the data acquisition system (see Section 3.4). Figure B.1 shows a photograph of the test set-up. The tip of the potentiometer was then lowered to the plate at a corner point on the 12"x12" grid and zeroed out. By moving the deck on the machine, the tip of the potentiometer was located at each point on the grid and at each point a reading of the length change of the potentiometer was taken.

These readings were compared to the zero reading of the potentiometer to generate a relative displacement from zero at each point on the grid. Through various mathematical transformations, the readings were referenced to a "best-fit plane". Points on the grid were measured off of that plane and plotted using the Excel spreadsheet graphics capabilities. Figure B.2 shows a 3-D plot of the as-delivered surface of one of the plates.

The previously described procedure was conducted on all nine (three per grip) plates before the start of the flat plate connection tests. These measurements showed that the plates, in their as-delivered condition, were quite flat. Typical maximum out-of-flat values were less than 0.02 inches. Several plates, namely the plates of the 2" grip, were measured again after the first 2" calibrated wrench test (CFCWNS-2). The results of these tests showed very little change in the "flatness" of the plates and it was believed that similar results would be forthcoming for the thicker plates of the larger connection grips. The tests themselves were very time consuming to complete. The results of the tests were found to be worth substantially less than the time and effort it took to produce them and this measurement program was discontinued. Plate out-of-flatness was no longer checked for the flat plate tests and was monitored by the simplified method described in Section 4.3 for the deformed plate tests.

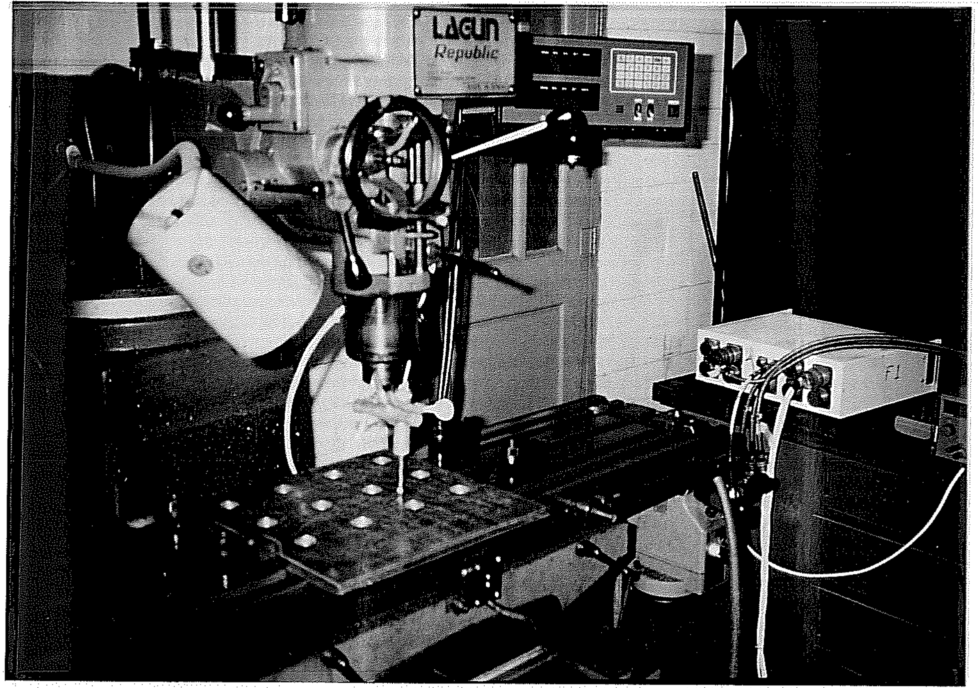


Figure B.1: Set-up for plate out-of-flatness measurements

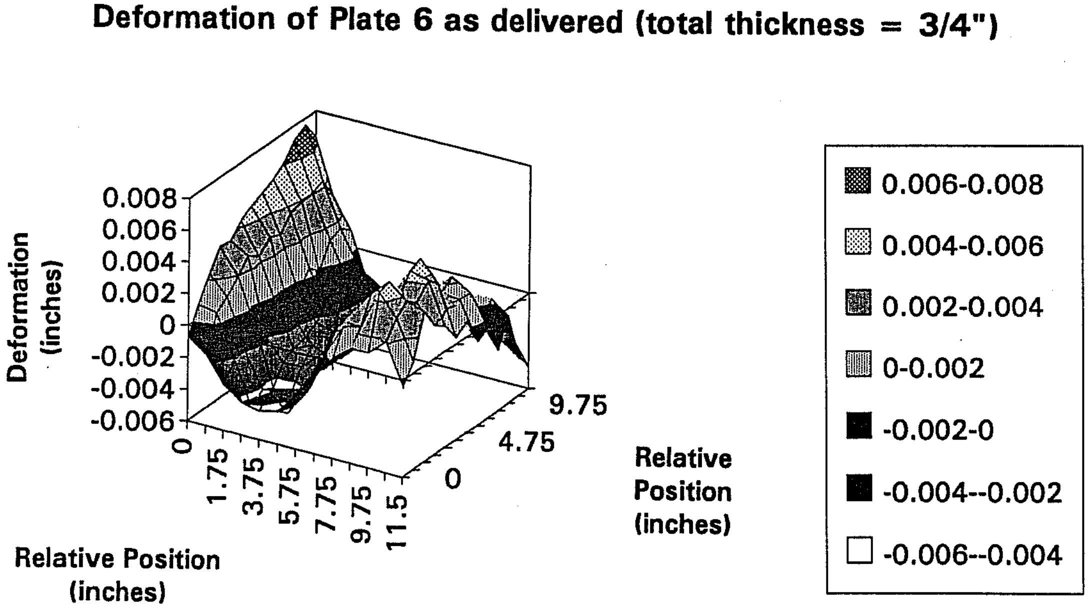


Figure B.2: 3-D plot of the surface of plate #6

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VITA

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