FINAL REPORT Phase 1

INSTALLATION CHARACTERISTICS OF ASTM F1852 TWIST-OFF TYPE TENSION CONTROL STRUCTURAL BOLT/NUT/WASHER ASSEMBLIES

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PREFACE

The evolution of the high strength bolts as alternative fasteners for hot driven rivets has continued with the development of sophisticated specialty fasteners and components that assist the user in the design, employment and inspection of construction. The tension control or TC twist-off type bolt had been considered an alternative fastener under the Research Council on Structural Connections Specification until it was covered under ASTM F1852 and later in the RCSC Specification, 2004.

Its popularity and broadening usage, particularly in the United States brought forward questions about the application of Specification Requirements on the procedures for use, inspection and quality control of installed tensions for slip critical and pretensioned joints. This research, the second project funded by RCSC on these fasteners, is attempting to resolve field practice issues relating to the use of these fasteners and to obtain data on the current characteristics of these fasteners.

The current research conducted at the University of Toronto has provided support for one Master of Applied Science student, Weiyan Tan and the summer support of an undergraduate student, Vladimir Maleev working with Ms. Tan, as a research assistant and later using the data and doing additional testing as his undergraduate (fourth year) thesis.

This research was carried out with direct funding from the Research Council on Structural Connections and voluntary provision of specimens and services from Walters Inc., Hamilton, Ontario and Tresman Steel Ltd., Brampton, Ontario. Equipment and technical support were, in part, provided by the University of Toronto, Department of Civil Engineering and the inventory of specialty apparatus developed over the years with the support of The Natural Sciences and Engineering Research Council of Canada and the Structural Steel Education Foundation of the Canadian Institute of Steel Construction. Test samples were generously provided by various member producers and suppliers of structural bolts in Canada and the United States.

ABSTRACT

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The growing use as a popular method of bolt installation of the ASTM F1852 Twist off Tension Control Bolt Assembly as covered in the RCSC *Specification for Structural Joints Using ASTM A325 or A490 Bolts* has led to issues being raised on the interpretation of the field installation requirements. The research that is reported here is the culmination of extensive testing of the effects of variables including field conditions or weather, atmospheric exposure, and installation practice. The goal or this research is to provide information on installation parameters to produce a repeatable installed tension in fasteners that meets the level required in the design.

Earlier research had shown that bolts placed in the steelwork and left for a period of time, prior to the final installation to a residual tensile force, experience degradation in the achieved tensile force that is attained and this is delay phenomenon forms the principal parameter of concern in this investigation. Other important parameters that were identified are the temperature of and moisture present in and around the fastener assembly at the time of final installation, the strength of the assembly and the configuration of the assemblies during atmospheric exposure.

The actual lubricant applied to the nut and is only defined in terms of its requirement to be dry to the touch and by the final performance requirements of the assembly, so several products were examined in the study. The results of all parametric variations are discussed and recommendations for improved specifications and procedures are made. Special attention is given to cold environment installation as one of the recommended topics for future research.

Table of Contents

List of Figures

List of Tables

NOMENCLATURE

A_b = body cross-sectional area

A_s = effective cross-sectional area of threads

β = the half-angle of the threads (30^o for UN or ISO threads)

D = nominal diameter

D_U = multiplier that reflects the ratio of the mean installed bolt pretension to the specified minimum bolt pretension

E = Modulus of elasticity

F_p = preload created in the fastener

H_h = thickness of the head of the bolt measured from the bottom

H_n = thickness of the nut

K = nut factor (on the order of 0.2 for high strength structural bolts)

K_b = the stiffness of the bolt

K_u = bolt stiffness obtained from linear regression analysis of unloading data

K_u^o = average bolt stiffness obtained from linear regression analysis of combined unloading data with the best fit line being forced through the origin

k_s = slip coefficient

ΔL = bolt elongation

ΔL_c = combined change in length of all sections

L_b = body length

L_{be} = effective body length

L_s = length of exposed threads

L_{se} = effective thread length

N_b = number of bolts in a joint

P = pitch of the threads

R_n = nominal strength (slip resistance) of a slip plane

r_n = the effective radius of contact between the nut and joint surface

r_t = the effective contact radius of the threads

T = tensile preload in the bolt

T_c = pretension achieved in steel joint

T_{in} = torque applied to the fastener

T_m = specified Minimum Pretension (28 kips)

T_u = ultimate strength form Direct Tension Tests

μ = mean slip coefficient for class A, B or C, faying surfaces, as applicable, or as established by testing in accordance with Appendix A of the RCSC specification

μ_t = the coefficient of friction between nut and bolt threads

μ_n = the coefficient of friction between the face of the nut and the surface of the joint

Y = the Y-intercept obtained from the linear regression analysis of unloading data

1. INTRODUCTION

1.1 GENERAL BACKGROUND

Bolt pretension is crucial in attaining the desired behavior in many structural connections used in steel construction. The slip critical and pretensioned (slip is not a criterion) connections require that a specified value of pretension be achieved during the installation phase. Specifically, the use of bolt pretension improves the behavior of connections subject to impact or cyclic loading, connections using oversized or slotted holes, shear connections proportioned for seismic requirements and all connections resisting crane loads (CSA S16-01 Standard, 2004). An example of a connection in a bracing member is shown in Figure 1.1. Splices in bridge girders, column splices, and tension hanger joints are additional specific examples.

Figure 1.1 Shear connection in a bracing member

In general, to obtain proper pretension, high strength bolts must be used. The preload is achieved by turning the nut or the bolt against the gripped material, while rotationally restraining the other part of the assembly, which results in bolt elongation. The tightening process is complete when a tension equal to or greater than 70% of the specified minimum tensile strength of the bolt is achieved (CSA Standard, 2004).

Failure to achieve the required bolt pretension could lead to serious and undesired structural behavior. For instance, the repeated slip of a joint could lead to unwanted displacements in the structure or even a fatigue-type failure of the connection. In addition, the effectiveness of pretensioned bolts as means for dissipation of energy under cyclic earthquake loading would be reduced, if the proper preload were not obtained. Increased displacement in column connections that could lead to additional second-order bending effects is one more example of these detrimental effects. Finally, vibration loosening and loss of the nut may occur, if the required minimum pretension is not reached.

According to the RCSC Specification (2004) there are four installation methods for pretensioning of high strength bolts:

(i) Turn-of-nut method — a simple and reliable method that relates the turns of the nut relative to the bolt from a snug-tight condition; pretension through bolt elongation to a tension level above the torqued-tension proportional limit of the bolt. The number of turns required varies with the grip length of the bolt. The use of this method requires that a sufficiently small component of torque is applied to the bolt during the installation to permit proper tension development during the combined experience of torque and tension. Generally, the "as-received" condition or that associated with moderate weathering of the assembly provides acceptable behavior.

(ii) Use of direct tension indicators ASTM F959 — a washer with arc-shaped protrusions is used. The deformation or flattening of these protrusions when tightening the bolt is correlated to the pretension force that is achieved during the installation.

(iii) Tension-control using twist-off ASTM F1852 fasteners — this method for achieving desired pretension uses a bolt/washer/nut assembly with a specifically configured bolt and wrench. The fastener has a splined end protruding beyond its threaded portion. The wrench has two coaxial chucks that react against one another during the development of the torque required to twist off the spline. The inner chuck engages the splined end while the outer torques the nut. The bolt assembly, as part of manufacture including lubrication, performs so that the splined end shears off at some point after minimum pretension is achieved.

(iv) Calibrated wrench — this is a method that is recognized by RCSC and is similar to the tension control method but can be applied to any bolt assembly after calibration at the jobsite to determine the torque required to achieve proper pretension. This torque may be adjusted so that an impact wrench stalls at that value or an electrically or hydraulically powered wrench stops automatically when the torque is reached. Previous research (Kulak, 1994) has shown that the pretensions achieved by this method are highly dependent on the frictional condition of the bolt assembly at the time of final torquing.

This study investigates the behavior characteristics of ASTM F1852 tension control, “twist-off”, fastener assemblies.

1.2 EXPERIENCE WITH TWIST-OFF BOLTS

As mentioned earlier, “twist-off” bolts differ from conventional fasteners in that they have different geometry and require special tools for installation. Use of these assemblies also offers three additional benefits: firstly, a single person can perform the installation since because the bolt is held by the wrench. Secondly, the process is quieter and typically uses a lighter wrench compared to the other methods. Thirdly, following pre-installation calibration, inspection is straightforward because the severed end indicates that proper pretension was achieved at installation. An additional feature is that if there is a concern regarding the achieved preload, the bolt could be tightened reliably as a conventional high strength bolt by the turn-of-nut method. Figure 1.2 shows a typical twist-off type assembly before installation.

These advantages have led to the increasing popularity and use of “twist-off” tension control bolts throughout Japan, Britain, United States, and recently in Canada. The Research Council on Structural Connections (RCSC) specifies that at least three bolts of each diameter, length, grade and lot be tested in a tension calibrator to verify that appropriate pretension is developed just prior to the installation. The current requirements of pre-installation verification were based on earlier findings (Kulak, 1994) on delayed installation.

Figure 1.2 Typical twist-off bolt assembly (ASTM F1852)

The principal factor affecting the behavior of these fasteners is the torsional response caused by the total friction caused at the face of the nut and between mating threads of the assembly. As a result, any condition that would affect this total friction may influence the achieved pretension. Therefore, questions have been raised about the performance of these fasteners in the field where there may be a significant variability of moisture, temperature, etc., when the bolts are finally installed. Also, in steel construction, it is typical that while the steel is being erected, the bolts are just loosely put into place until all the elements are aligned properly. The assemblies may be snug tightened, usually at time of erection, but it could be days or weeks before a bolt crew actually completes the installation with the final pretensioning. The resulting time delay during which the assemblies are exposed to the weather and construction site conditions may change their installation characteristics. For example, this exposure to weather could lead to deterioration of the thread and nut lubricant conditions and affect the frictional performance of the assembly. In addition, questions have also been raised about the variability in performance of the tension calibrators that are used in the field to do the required pre-installation verification.

Test data from laboratory research has indicated that the mean value of the installed pretension is different for each of the bolt installation methods. When the turn-of-nut method is used to install ASTM A325 bolts, the mean pretension is about 1.35 times the specified minimum pretension. When the calibrated wrench method is used, the mean pretension is only about 1.13 times the specified minimum pretension. In case of the twist-off tension-control bolt assemblies, the achieved pretension varies with the bolt manufacturer, the time delay at installation and environmental conditions of storage and exposure vary. Field test data on achieved bolt tensions are only available for turn-of-nut pretensioning, and Direct-Tension-Indicator pretensioning (Kulak and Birkemoe, 1993). The mean value of pretension was about 1.27 times the specified minimum pretension. It confirmed that the field practice was achieving bolt tensions that were comparable to the extensive laboratory studies that had been conducted to develop the installation methods. The use of an ultrasonic bolt length measurement device, was featured in this field study, since this technique made it possible to determine bolt pretensions in the field in a convenient and reliable way.

1.3 OBJECTIVES AND SCOPE

The convenient one person installation and the simple visual inspection make the twist-off tension-control bolts attractive to erectors, inspectors, as well as designers. However, since the pretension is achieved through a torque control that is built into the twist-off bolt assembly, various factors that cause variation in pretensions of bolts installed with torque control method will affect the pretension developed in twist-off tension-control bolts. The obvious factors that affect the pretension of twist-off tension-control bolts are the bolt material strength, geometric properties of the bolts, thread conditions and lubrication conditions at the bolt and nut threads as well as the washer under the nut. One of the main objectives of this research is to examine the effects of these parameters on the bolt pretension. A series of test programs were performed to that end. In addition, although reuse of the ASTM F1852 twist-off tension-control bolts is not explicitly stated in the current RCSC Specification (2004), it is considered that the provision for reuse of black A325 heavy-hex structural bolts is also applicable to ASTM F1852 twist-off bolts because of their similar dimensional and material properties. Some tests were conducted to investigate the rotational capacity of the twist-off bolt and to directly compare the twist-off tension-control bolt pretensioning results with those from the turn-of-nut technique.

The main objective of the research is to perform an extensive testing to evaluate the pretensions achieved by twist-off tension-control bolts and determine the significant parameters related to the impact of the field environment on their performance. The pretension achieved in twist-off tension control bolts in the field is questioned because of the delayed installation that is typical in practice. Usually twist-off tension-control bolts will be tightened with the special installation wrench to shear off the splined ends a few weeks after they are inserted into the bolt holes and snug-tightened using a hand wrench. During this delay period, the lubricated and unlubricated condition of the critical surfaces of the nut, bolt and washer may change. To investigate the effects of delayed installation, a group of tests were conducted on 3-plate joints placed on the roof of Galbraith building (GB) on the University of Toronto campus at 35 St. George Street, Toronto, ON. In addition, since the main concern in not obtaining the required pretension is the occurrence of slip, the effects of rusting of steel plates on the coefficient of friction in slip critical connections will be observed. The requirement for field verification of the performance of fasteners that had experienced a delay in final tightening after initial placement in the steel work suggested that scrutiny of the verification technique should be included as a significant objective.

This research further demonstrates the feasibility and reliability of using the ultrasound technique to establish elongation and thus the pretension in the twist-off tension-control bolts. The Bolt Gage was used to measure the bolt length in the loaded and unloaded condition and thus determine the pretension in the fasteners based on the knowledge of the bolt stiffness. Comparison of the pretension data results from the Bolt Gage, strain-gaged bolt, and Skidmore-Wilhelm bolt tension calibrator, was also made to show the accuracy of the technique. Moreover, as the change in bolt length can be monitored with the Bolt Gage immediately after and even during the tightening procedure, the elastic interaction between bolts in a joint as well as the relaxation effect can be captured and thus taken into account in the residual measured pretension of the bolt.

1.4 SYNOPSIS OF THE REPORT

Chapter 2 focuses on literature survey of various methods to effectively control the bolt pretension. The results of previous research conducted to study the of twist-off tension-control bolt are also reviewed. The technique of utilizing the Bolt Gage to establish bolt pretension in the field test is reviewed in detail and the concept of stretch control of bolt pretension measurement method and the use of the Bolt Gage are explained in Chapter 3. A mathematical model to calculate the bolt stiffness theoretically is proposed, and physical laboratory testing to determine the bolt stiffness is also reviewed in detail. In Chapter 4 various experiments, carried out in this research to investigate the of twist-off tension-control bolt assemblies, are discussed. Chapter 5 contains conclusions of the research programs and recommendations for future research.

2. THEORY AND LITERATURE REVIEW

This section presents the theoretical background to bolt pretension as well as a review of related research. Literature on fundamentals and previous work on bolt pretension control methods: torque control, turn-of-nut control, tension control, and stretch control are discussed in the following.

2.1 BOLT PRETENSIONING METHODS

The general bolt tightening procedure is well described by Bickford (1995) as: “a certain amount of torque is applied to the nut, the nut turns, the bolt stretches, and thus creates preload”. Through this procedure it is generally possible to control the bolt pretension by torque, by turn, or by stretch. Additionally, the pretension can be measured directly and indirectly with some calibrated measurement techniques.

ASTM F1852 TC (twist-off type tension control) bolt assembly, the target bolt of this research, used a torque control led installation. The method used to evaluate the pretension of this product in this research is that of stretch monitoring (elongation control) with the Bolt Gage. In addition, the reinstallation of an ASTM F1852 TC bolt assembly using a turn-of-nut installation method is also important if these fasteners must be reused or retensioned. With consideration of all these concerns about ASTM F1852 TC bolts, the related bolt pretension control methods: torque control, stretch control, and turn-of-nut control are reviewed here in detail. The other pretension control method, tension control, is also introduced briefly. The strain-gaged bolt, one of the applications of tension control method, was used in this research to compare with the pretension results from the Bolt Gage. Additionally, the established bolt installation methods in the RCSC Specification (2004) are surveyed for a better understanding of the current requirements for TC bolt installation.

2.1.1 Torque Control

The torque control method was primarily used in the bolt installation when the high strength bolt was first introduced. Torque control was and is popularly used in many mechanical applications and is particularly effective at lower levels of pretension and for use in repetitive, closely monitored, manufacturing operations.

Laboratory and field tests as well as theoretical analysis show that the torque-tension relationship appears to be a linear one in general as established by simple rigid body statics, but it exhibits great variability in the test results when high pretension is the objective. This variance is caused mainly by the variability of the thread conditions, non-linear local behavior and relative straining between contacting elements, surface conditions under the nut, lubrication, and other factors that cause energy loss other than that for inducing tension in the bolt (Kulak et al., 1994).

There are two well-known equations that are used to calculate the amount of the pretension achieved after the bolt is tightened by a certain amount of input torque. One of the equations was proposed by Motosh (Shigley, 2001)

$$T_{in} = F_p \left(\frac{P}{2\pi} + \frac{\mu_t r_t}{\cos\beta} + \mu_n r_n \right) \tag{2.1}$$

where,

T_{in} = torque applied to the fastener

F_p = preload created in the fastener

P = pitch of the threads

μ_t = the coefficient of friction between nut and bolt threads

r_t = the effective contact radius of the threads

β = the half-angle of the threads (30^o for UN or ISO threads)

μ_n = the coefficient of friction between the face of the nut and the surface of the joint

r_n = the effective radius of contact between the nut and joint surface

with consistent force and length units used throughout.

This equation is one of the so-called “long-form” equations. It apparently shows that the input torque is resisted by three reaction torques: the bolt stretch component of the reaction torque, the reaction torque created by frictional restraint between nut and bolt threads, and the reaction torque created by frictional restraint between the face of the nut and the washer or joint. Typically, the nut friction torque is approximately 50% of the total; thread friction torque is another 40%, and the bolt stretch component is only 10%.

There are many factors that affect the torque-preload relationship. First of all, the variables that affect friction include: the hardness of all parts; the surface finishes; the type of materials; the thickness, the condition, and the type of coating; the type, the amount, the condition, the method of application, the contamination, and the temperature of the lubricant; the nut tightening speed; the fit of the threads with respect to tolerances; the hole clearance; and the presence or absence of washers. Secondly, there are the geometric variables. In practice, there are many variations in the pitch of the threads, the angle of the threads, and in the effective contact radii between parts. For example, the face of the nut is seldom exactly perpendicular to the axis of the threads; the holes are seldom drilled exactly perpendicular to the surface of the joint, so the actual contact radius r_n (the effective radius of contact between the nut and joint surface) is usually unknown. The geometric factors r_t (the effective contact radius of the threads) and pitch can also be changed by the plastic deformation with severe local stress concentrations in portions of the bolts, as in thread roots and the like. Thirdly, there are other factors that are not present in Equation (2.1). When the nut is tightened, only part of the input work ends up as bolt stretch or friction loss. Other parts of the input work would end up as bolt twist, a bent shank, nut deformation, and joint deformation. Moreover, there are additional things that have some influence on the torque-pretension relationship. These include: the hole interference, the interference fit of the threads, operator skill, tool accuracy, installation procedure, relaxation, etc. Another torque-tension equation is the “short-form” equation. It generalizes all the factors which affect the torque-pretension relationship into a dimensionless factor called “nut factor”.

$$T_{in} = F_p \times (KD) \tag{2.2}$$

where,

T_{in} = input torque

F_p = achieved preload

D = nominal diameter

K = nut factor (on the order of 0.2 for high strength structural bolts)

The nut factor K is an experimentally determined constant. A given or arbitrary value such as “0.2” above is not appropriate for installation of structural bolts to a specified pretension level.

As illustrated in the Guide (Kulak et al., 1994), tests performed by Maney, and later by Pauw and Howard, showed a great variability of the torque-pretension relationship. Bolts from the same lot produced extreme pretensions 30% from the mean pretension required. The average variation was in general 10%.

Calibrated Wrench method

Among the bolt installation methods allowed in the RCSC Specification, the calibrated wrench method is a torque-controlled method of installation. All the variables that affect the relationship between torque and pretension, as described previously, influence the bolt pretension results of this installation method. The scatter in installed pretension can be significant. Calibrated wrench pretensioning method had been removed in the 1980 edition of RCSC Specification, but was reinstated in the 1985 edition with more restrictive requirements.

In the calibrated wrench method the wrench is calibrated to stop automatically or in the case of an air impact wrench, to stall when the required torque is reached. RCSC Specification (2004) stipulates that each day, and for each different diameter, length, and grade of bolts, a representative sample of not fewer than three bolts must be selected and used to calibrate the wrench. The bolts are tightened in a calibrating device, usually the Skidmore-Wilhelm bolt tension calibrator, at the site of installation to measure how much torque is required to tighten the bolts to tension that is greater than or equal to the required pretension. The wrench is set to stop at that torque and all bolts from that lot on that day are installed to that torque condition after the joint is snug-tightened first. Wrenches must also be calibrated when the particular lot of any component of the fastener assembly is changed, relubricated, or when significant differences in the surface condition of the bolt threads, nuts, or washers occur. This is also true when any aspect of the wrench is altered or adjusted. To minimize the variation in friction, fastener components should be protected from contamination by dirt and moisture as required in the RCSC Specification (2004), and a hardened washer must be used under the turned part during the tightening. The element not turned by the wrench is prevented from rotating during the tightening. The inspection requirements for the calibrated method consist of monitoring the pre-installation verification testing to make sure that the installer properly applies the calibrated wrench to the turned part by routine observation, and to confirm that the time between removal from protected storage and the final pretensioning is within limits. After the inspection, the arbitration procedure described in the Specification can be performed when the pretension developed in the bolts is questioned.

Tables, although frequently available and relating torque to pretension are not applicable; this practice is not permitted by Canadian Standard CAN/CSA-S16.1-94 nor by the RCSC Specification (2004). Although torque control has been typically accomplished by adjusting air pressure to cause a pneumatic impact wrench to stall, electric and hydraulic wrenches using an adjustable torque sensor for cutoff may be used.

Twist-off Tension Control bolts

The twist-off type tension control bolt assembly is a torque control device where the torque is controlled within the fastener assembly and for structural applications is manufactured to ASTM F1852-98, (1998). The assembly functions by designing a combination of lubrication, bolt finish and spline end dimensions so that the torque needed to twist off a splined extension end of the bolt at a circular notch (torque control groove) happens after the bolt achieves the desired tension. The torsional shear-off of the splined end thus occurs at a bolt tension above the minimum required pretension if the bolt was made correctly and if the desired frictional performance at the thread and nut face is present. All of the fastener assembly variables that affect the torque-pretension relationship, as discussed, are applicable to the ASTM F1852 TC bolts. As required in the RCSC

Specification, twist-off type tension control bolt assemblies must be used in the as-received, clean, lubricated condition.

The twist-off tension control bolt is pretensioned from one side (the nut side) only. The bolt is held by a special wrench from the splined end rather than held or turned from the round head. This specially designed electrically powered wrench contains a two-part socket that can hold the bolt at the splined end as well as turn the nut. A typical installation is done in two steps. First, the joint is compacted to a snug-tight condition without damaging the splined end, with washer placed under the nut as part of the bolt assembly; a spud wrench may be used or the assembly can be tweaked with the installation wrench. The bolts in the joint are then fully pretensioned by systematically twisting off the splines with the special wrench. The whole installation procedure should progress systematically from the most rigid part of the joint to minimize the interactive effect where the tension in a fastener may be altered by the tightening of an adjacent fastener. Pre-installation verification must be performed and the operation inspected as stipulated in the RCSC Specification. This inspection is to verify that the pre-tightening or snugging up of the joint is done prior to installation and that the splined ends are removed after the final installation. An arbitration procedure is applicable to twist-off bolt assembly when the adequacy of the bolt pretension is questioned.

In the current RCSC Specification (2004), ASTM F1852 (1998) twist-off type tension control bolt assemblies are recognized directly, while the use of other twist-off type tension control bolt assemblies that meet the detailed requirements of alternative-design fasteners described in the Specification is also considered acceptable. If galvanized, ASTM F1852 twist-off bolt assemblies are required to be mechanically galvanized; typically, different lubricants would be used. ASTM F1852 twist-off bolts are permitted to be reused as heavy-hex structural bolts, but since the spline is removed in the first installation, an alternative installation method must be selected. While turn-of-nut is likely the method of choice, the question of backing up the bolt in the absence of the hex on the button head end presents a problem. Some manufacturers have provided an embossment on the contacting bearing surface of the head or an alternative design head fixturing. Of course, the F1852 bolt may be produced with a standard hex head.

The quiet and easy one-side installation as well as the simple visual inspection are the attractive features of the twist-off tension control assemblies. However, the price of twist-off bolts is higher than that of conventional high-strength bolts, the proper disposal of the sheared spline ends must be done for safety, and bolt pretension actually achieved in the field installation will only be adequate if it is properly verified before installation and if the correct installation methods and procedures are used.

2.1.2 Turn-of-nut Control

As noted in the previous section, there are some precautions and concerns when torque is used as a means of controlling the pretension of high strength bolt. To overcome the variability of torque control, turn-of-nut method was introduced; this technique is based on the application of a specific minimum elongation.

In theory, turn-of-nut control was originally a torque-turn control technique. The procedure is performed as follows: the nut is first snugged with a torque to bring the connected parts into solid contact. Then the nut is turned a third or a half (depending on the bolt length) turn relative to the bolt; this is enough to stretch the bolt past its proportional limit. The initial snugging process torque is used to compensate for start-up variables, such as the slip of the bolt head, a bent washer, the out-of-flatness of the joint members, etc. that would require more than the specified turns to reach the required minimums. The actual load achieved at this initial stage is not relevant, rather, only the contacting of the steel parts is a concern. Turning the nut to elongate the bolt a specific amount provides the final control of elongation. It is argued that the turn control is better than torque control, because the relationship between the relative turn and pretension is not significantly affected by friction unless the thread friction is extremely high.

In current RCSC Specification (2004), the nut is first run up to a snug position, and then the nut is given an additional amount of turn, depending on the length of the bolt. The snug tight condition is defined as the tightness that is attained with a few impacts of an impact wrench or the full effort of an ironworker using an ordinary spud wrench to bring the connected plies into firm contact. This definition is applicable to all cases, but the amount of rotation required beyond snug differs for different bolt diameters and lengths. Both the snug-tightening procedure and the subsequent additional turning process must proceed systematically from the most rigid part of the joint to minimize relaxation of the previously tightened bolt. In most cases, washer is not required, since the frictional resistance of the bolt assembly is of less importance.

After snugging the joint, the bolt shank and nut may be marked as a later indication that the required relative rotation had been applied. The amount of rotation is usually controlled by visual observation of the wrench socket; special wrenches can be set to stop at a specific rotation. The correct snugging of the joint and restraint of the bolt head from turning during the final installation step are the two main parameters for successful turn-of-nut pretensitoning. Theoretically, two persons are required to execute this method correctly: one holds the bolt from turning and the other person operates the wrench. In practice the bolt rarely turns if not backed up and the turn relative to the nut can be verified with pre-marking; as a result, a one person can perform the turnoofonut bolt installation.

The RCSC Specification (2004) requires that not fewer than three bolts of each diameter, length, grade and lot that are to be used on the work site must be checked in a tension calibrator prior to installation. During the stipulated procedure, the bolts must achieve a pretension that is at least 1.05 times the specified minimum pretension. If the test of any of the bolts results in a pretension less than the required amount, cleaning, lubrication and retesting of the bolts are allowed with the provision that all bolts of that group are modified in the same manner. After such modification the test would be repeated.

The main requirements for inspection given in the RCSC Specification, are to check that all fastener components, all connected plies and all bolt holes meet the requirements prior to the start of the work, and after the assembling of the connection to observe that the plies of the connected elements have been brought into firm contact and washers have been appropriately placed after snugging. The inspector shall observe the pre-installation testing and carry out routine observation to monitor the turning process.

The turn-of-nut method may not always work correctly, sometimes (e.g. when hot-dip galvanized bolts are used) the tension may not be achieved in the specified turns. The problems may be caused by a very effective lubricant; if the lubricant reduces the coefficient of friction between the bolt and the nut so much that the full effort of an ironworker using an ordinary spud wrench for snug-tightening the joint may for smaller diameters produce the full required pretension. Thus, the highly lubricated high-strength bolts may require a very small torque to produce the specified pretension. On the contrary, the lack of lubrication or improper over-tapping can lead to seizing of the nut and bolt threads; this in turn may result in a torsional shear failure of the bolt before the specified pretension is reached. These potential problems can be caught and dealt with during the pre-installation verification required in the Specification.

Generally, at the snug-tight condition, the pretensions developed in the bolts vary greatly as the elongations are still within the elastic range. After the nut rotates from the snug-tight condition to the specified turn, the elongation enters the plastic region where the load versus elongation curve of the bolt softens; because of this limiting material characteristic there is very little variation in the pretension achieved within a typical lot of bolts. The turn-of-nut method is considered to be a strain control, or elongation control method. Compared with the calibrated wrench or torque control methods, this strain-control method yields more consistent bolt pretensions.

2.1.3 Tension Control

Ideally, direct control by measuring and applying tension may be the best way to control the bolt pretension directly, but in fact, there is no practical method to measure bolt stress or bolt tension directly in most bolting applications. Anchor rods and certain large mounting bolts may be loaded with a jack by the direct application of a measured force, followed by adjusting the nut to maintain that force. Nevertheless, some techniques that are very close to tension control are now used in some cases.

Direct Tension Indicator

Direct-Tension-Indicator pretensioning is one of the installation methods introduced in the RCSC Specification. ASTM F959 (1999) direct tension indicators are accepted as a compressible-washer-type bolt tension indicating device in the specification. Direct tension indicators are round hardened washers that have a series of arch-like protrusions on one face which form a gap between the fastener bearing surface and a hardened washer (usually under the bolt head). As the nut is tightened, these protrusions yield plastically and become flattened. Bolt tension is evaluated by the deformation of the washer, regardless of the torque resistance of the bolt. When the gap between the head of the bolt and the washer is reduced to a prescribed value, the tightening process is stopped and the bolt is considered to be properly tightened.

A series of experiments have been made to evaluate the accuracy of Direct-Tension-Indicator pretensioning method. Test results showed that the minimum tension required was achieved. The accuracy ranged from +4%, -6% to +12%, -10% when DTI's were used between parallel joint surfaces (Bickford, 1995). As the measurement of the collapse gap is related to bolt pretension directly for a given washer, the accuracy result is in no way affected by the bolt parameters. But, as can be said for all methods, the load indication is the load at the time of installation and would not change if the bolt tension subsequently diminished.

Strain-gaged Bolts

Instead of measuring tension directly, measuring the strain with electronic resistance type strain gages is perhaps the most accurate way to determine the tension by correlating it with strain through direct calibration experimentally. Due to the relatively high cost, the strain gage technique is not considered to be a practical way to measure tension and is not effective in a multi-fastener application. To measure the average tensile strain in bolt, a group of strain gages must be carefully placed on the prepared portion of the unthreaded bolt shank with consideration of temperature compensation. Precalibrated, strain gaged bolts can yield a preload accuracy of 1-2%, however, the strain gaged bolts are only used for specific applications because of the various application problems with strain gage techniques (examples include the delicacy of the wires used to connect the gages to the readout instrument, and the requirement of access to the bolt shank, or sometimes even a central axial hole in the bolt for larger diameter bolts). Other special gauges are available for mounting in a small hole along the axis of the unthreaded shaft, but these too were not considered practical for this research.

2.1.4 Stretch Control

The idea of stretch control based on the fact that bolts in joints act like stiff springs. The relationship between the change in length of the bolt and the bolt preload can be described by the equation below, i.e. the change in length of a bolt is equal to the bolt preload times a constant which can be determined in terms of bolt properties and dimensions using Hooke's law.

$$\Delta L_c = F_p \times \left(\frac{L_{be}}{EA_b} + \frac{L_{se}}{EA_s} \right) \tag{2.3}$$

where,

L_{be} = effective body length

A_b = body cross-sectional area

E = Modulus of elasticity

L_{se} = effective thread length

A_s = effective cross-sectional area of threads

ΔL_c = combined change in length of all sections

F_p = preload in the bolt

with consistent force and length units used throughout.

Compared with Equation (2.1), the long form relationship between the input torque and the bolt pretension, the relationship shown in Equation (2.3) eliminates most of the factors that cause control problems when torque control is used. Equation (2.3) implies that the preload can be determined with the same degree of accuracy with which the bolt elongation is determined. It also infers that relationship between bolt preload and bolt elongation is elastic and that it will be affected by variations in the effective threaded length during installation.

The following are some of the variables that affect the relationship between bolt preload and bolt stretch:

Dimensional variations

Although a bolt is a highly standardized product, variations within the manufacturing tolerance exist. Some analyses indicate that the possible preload scatter because of dimensional tolerances is only about 2.7%, as the dimensional variations are not a major source of error (Bickford, 1995).

The temperature effect

The change in temperature of the bolt relative to the steel work can induce another type of dimensional variation: thermal expansion or contraction. The heating up of a bolt during installation will thus influence the final tension.

Variations in bolt stress level

Equation (2.3) considers the bolt as two cylinders in series, each with uniform stress distribution. In reality, the nature of stress distribution for each bolt is quite similar, but the stress magnitude varies widely because of variations in geometry, material, heat treatment, and tolerance between nut and bolt threads. Variations of stress distribution from the ideal can induce scatter between the calculated and actual preloads. The results of some tests performed to determine the relationship between applied tension and bolt elongation showed that even a small change in thread pitch can have a significant effect on results, and the slope of the tension-elongation curve for a specific bolt appeared to be a little less stiff with each successive loading (Bickford, 1995). During the beginning of first loading it is likely only one or two threads carried the load, while after the first loading, the threads likely yielded a little, and the subsequent load was distributed more uniformly over the threads, thus gradually increasing the effective length of the bolt. The preload scatter can be reduced to about 5%

by measuring the bolt stiffness in the tensile machine after the first loading of the bolts, and taking the mean slope of several sample bolts selected randomly from the bolt group.

Bending and non perpendicular surfaces

In reality, the bolt tends to bend to some degree, because the joint and nut surfaces are never exactly perpendicular to thread axis nor parallel to one another. A bolt almost never stretches uniformly (without inducing flexure) when it is tightened. Bending changes the stress patterns in bolt, and hence the stretch . Although no evidence showed that bending was severe enough to cause a big preload scatter, it can be a problem.

Grip length

The bolt tension-elongation relationship is a function of the grip length, the combined thickness of the plate members. The bolt stiffness will increase as the grip length decreases. Although there will be some manufacturing tolerance on the thickness of the plate members, the resulting change in grip length will not produce a major error in load estimation.

Stretch control makes it possible to measure the residual pretension after the bolt has been tightened. Stretch control is not intended as an alternative installation method, but rather it is suggested as a research tool. It does not provide perfect estimation of bolt tension, but accuracy is second only to the strain calibrated bolt shank. Furthermore, when stretch control is combined with the accurate ultrasonic measurement of bolt length or bolt elongation, the bolt stretch can be read during and after tightening or before and after loosening. With TC twist-off bolts, only the shortening measurement on loosening after installation is practicable.

2.2 TWIST-OFF TENSION CONTROL RESEARCH

Only a few reports on the of twist-off tension control bolts are available. The following are two recent reports on twist-off bolts. The first one is a University of Alberta report prepared by Kulak and Undershute (1994) that examined the strength and installation characteristics of TC tension control bolts. The second one is a Virginia Polytechnic Institute and State University report prepared by Murray and Schnupp (2003) that investigated the effects of head size on the performance of twist-off bolts.

2.2.1 University of Alberta Report (1994)

Sponsored by the Research Council on Structural Connections, Geoffrey L. Kulak and Scott T. Undershute performed a series of tests on tension control bolts with ASTM A325 mechanical properties to investigate the strength and installation characteristics of tension-control bolts. The main purpose of this research was to study the pretension of the tension control bolts from different manufacturers and with different aging, weathering, and thread conditions.

Bolts from by seven manufacturers were tested. The target bolts of this study were 3/4 in. diameter bolts with different lengths of 2 1/4 in., 2 1/2 in., 2 3/4 in., 3 in., and 3 1/4 in. and 7/ 8 in. diameter bolts with a length of 4 inches. The bolts were tested in two series: 1. bolts subjected to various conditions of exposure; 2. bolts with different kinds of friction conditions. The bolt pretensions were determined either by a hollow load cell for bolts installed in a solid piece of steel or in a simulated joint, or through a Skidmore-Wilhelm hydraulic bolt calibrator directly.

The preload results were given in this report as normalized preloads with respect to the specified minimum preload. The average normalized preload for those as-delivered bolts was 1.20, with a standard deviation of 0.11. Analyses of data from each lots showed that among those factors which will affect the bolt pretension, the lubricant quality and durability are more important than the age of the bolts, and the bolt strength can affect bolt pretension. As the bolt strength increases, higher bolt pretension can be achieved. For bolts stored indoor in a sealed metal keg for two and four weeks, the average normalized preloads were 1.16 and 1.20, separately, i.e. there was no significant decrease in bolt pretension, but long-term indoor storage in an unsealed keg may be detrimental. For bolts exposed to outside humidity for two and four weeks, with average normalized pretensions of 1.16 and 1.17, only a slightly decrease in bolt pretension was observed, and it was anticipated that longer storage periods in a humid atmosphere or higher humidity may result in lower preloads. For bolts with full exposure to weather, the two-week and four-week average normalized preloads were 1.12

and 1.10, respectively. The amount of rust and lubricant degradation affected the achieved preload greatly. For bolts snug-tightened in the simulated joint with full exposure to the weather, the two-week and four-week average normalized pretensions were both 1.05, this is the lowest bolt pretension attained among all different types of exposures.

In the slip-critical joint, the slip resistance of the joint is a function of the slip coefficient of the connected material and the bolt pretension. The actual slip probability varies with the bolt installation method when the slip coefficient is constant. For example, the turn-of-nut method yields a better slip resistance than the calibrated wrench method because of the higher mean pretension and the reduced variation. Comparisons among the pretensions achieved by turn-of-nut installation method, the calibrated wrench method, and the twist-off tension control bolt were also shown in the report.

For the tension control bolts tested in the as-delivered condition or after indoor storage in a sealed keg or after exposure to ambient indoor humidity, the lowest average normalized preload was 1.16. Thus in any of these three categories, the tension control bolts achieved average non-dimensionalized preloads between the average preloads of the turn-of-nut and calibrated wrench installation method. For tension control bolts exposed to outside atmospheric humidity, the normalized preload was as low as 1.03 in several cases. Since the average normalized preload was 1.16, in general, the preloads in tension control bolts were slightly higher than that produced by calibrated wrench installation method in the lab, and much less than that achieved by turn-of-nut method either in the lab or in the field. For tension control bolts with full exposure to weather, the average normalized preloads were measurably lower than those achieved by the turn-of-nut method, and a little lower than that by calibrated wrench method in the lab. For tension control bolts weathered in a simulated steel joint, the average normalized preloads were much lower than those obtained by a calibrated wrench method in the lab, and of course, a lot lower than those obtained by the turn-of-nut method.

The results of the friction tests showed that the lubrication condition of the bolt and nut threads as well as the washer played an important role on the attainment of bolt pretension. If the bolt assembly was intentionally cleaned of lubricant with mineral spirits, the average normalized pretension was only 0.81. This was significantly less than the as-delivered pretension value of 1.31 of the bolts from the same lot. Re-lubricating the bolt threads and washer with lithium grease and thread compound produced different pretension results of 1.14 and 1.52, respectively. If the as-delivered bolt assemblies were contaminated with dirt, the average pretension dropped to 1.17. If only the threads of the bolts were contaminated, the pretension was 1.27, which is very close to the as-delivered pretension. Further data analysis showed that the torsional friction at the nut-washer interface is about 90% of the total torsional friction. Proper lubrication at the nut/washer interface is a very important requirement for achieving the desired preload in tension control bolts.

Kulak and Undershute (1994) confirmed that the pretension obtained in tension control bolts strongly depends both on the friction conditions of the bolt/nut threads and the nut/washer interfaces. Both the lubricant quality and lubricant quantity are key factors in obtaining a well-lubricated bolt assembly. The authors also concluded that quality controlled manufacturing of all the parts of the bolt assembly as well as proper bolt installation are required to obtain the qualified performance of tension control bolts.

2.2.2 Virginia Polytechnic Institute and State University Report (2003)

Thomas M. Murray and Keith O. Schnupp conducted tests to study the effects of head size on the performance of twist-off bolts. In current RCSC specification, an ASTM F436 washer is required when there is oversized or slotted hole in an outer ply, but if the heads of tension-control bolts provide a bearing circle with a diameter that is equal to or greater than the diameter of the corresponding ASTM F436 washer, the washer can be excluded. The minimum bearing surface diameter allowed in ASTM F1852 is smaller than the nominal outside diameter of ASTM F436 washer. The purpose of this research was to examine the ASTM F436 washer requirement for oversized or short-slotted hole and determine whether or not it can be omitted for tension-control bolts with smaller bearing surface diameter.

Tests were conducted on tension-control bolts of A325 and A490 strength with diameters ranging from 5/8 in. to 1 1/8 in. The head bearing surface diameters of the tested bolts included both the minimum required diameter permitted by ASTM F1852 and the larger manufacturer's standard head diameter. A Skidmore-Wilhelm bolt tension calibrator (Model ML) was used to measure the bolt pretension. Additional plates with various holes, including standard, oversized, excessively oversized and slotted ones, were placed under the bolt head.

Test data indicated that bolts with the minimum bearing surface diameter on head attained the same pretension as those with the larger manufacturer's standard diameter, and the size of the hole in the plate had no effects on the bolt pretension. As the amount of the bearing surface under the bolt head did not appear to affect the achieved bolt pretension, a conclusion was made by the authors of this report that the pretension expected to be achieved in a bolt with the minimum head bearing surface diameter is the same as that in bolt with a larger diameter equal to that of a F436 washer, if the size of the hole is within the RCSC Specification limits on hole size.

2.3 REPORTS ON FIELD STUDIES OF BOLT PRETENSION

Two separate investigations on the pretension of high strength bolts in the field were conducted by two research groups: Team 1 (Peter C. Birkemoe and Nick Grgas) in University of Toronto and Team 2 (Geoffrey L. Kulak and K. H. Obaia) in University of Alberta. An ultrasonic bolt length measurement device called the Bolt Gage, was used by both teams to evaluate the pretension in bolts installed in the field. The tested ASTM A325 and A490 bolts were previously installed by the structure erector using turn-of-nut method.

The use of the Bolt Gage made it possible to reliably measure bolt pretension in the field in a relatively convenient way. After calibration and proper settings for electrical compensation of the Bolt Gage, the error of the established bolt pretension can be limited within 5%. First, the stretched length of bolts that had previously been installed in the field was measured by the Bolt Gage. Then length was read again from the Bolt Gage after the bolt was loosened by turning the nut. The bolt pretension was calculated with the change in length taken in the field and the bolt stiffness calibrated in the laboratory. The stiffness of bolt was determined from the direct tension test data in the unloading process. In the University of Alberta report, the bolt stiffness was taken as the mean value of measured stiffnesses of three individual bolts in a group. In the University of Toronto report, with the consideration of the slope of the tension elongation relationship as well as the Y-intercept, a method of establishing the bolt stiffness from the combined data of all three calibrated bolts was proposed. The linear regression analyses were able to represent the unloading curves very accurately. Due to the nonlinearity of the measured stiffness, the Y-intercept values were not zero, and changed from bolt to bolt. After a careful data analysis, the author recognized that when the unloading data for all the calibrated bolts in a group was combined for regression analysis, the Y-intercepts obtained were closer to zero than those calculated for the individual bolts. The stiffness and Y-intercepts, obtained from linear regressions of the combined data were used to establish pretensions of bolts installed in the field in this report.

The test results showed that the mean pretension of ASTM A325 bolts installed by turn-of-nut method in bridges is about 1.27 times the specified minimum pretension. This mean value of pretension was higher than those obtained from other building structures, and only slightly lower than that yielded from laboratory studies (1.35). In addition, the installation of ASTM A325 bolts by turn-of-nut method or by the use of direct tension indicators provided very similar results.

2.4 SLIP PERFORMANCE

Since the engineer’s main concern in not obtaining the required pretension is the occurrence of slip, it was considered important to also examine the environmental effects on slip resistance of steel plates. This is also an issue in the field, where the steel is specified as blast-cleaned, but at the time of inspection or pretensioning it has already begun to rust. Thus, some time was dedicated to comparing the slip behavior of rusted versus blast-cleaned plates.

According to the RCSC Bolt Specification, the nominal slip resistance, is expressed as

$$R_n = \mu D_u T_m N_b \left[1 - \frac{T_u}{D_u T_m N_b} \right] \qquad (2.4)$$

where T_u is the tensile component of applied factored load for combined shear and tension loading. To simplify, assume that the connection is loaded only in shear. Then equation 2.4 becomes:

$$R_n = \mu D_u T_m N_b \qquad (2.5)$$

where,

μ	=	Mean slip coefficient for class A, B or C, faying surfaces, as applicable, or as established by testing in accordance with Appendix A of the specification
	=	0.33 for Class A faying surfaces (uncoated mill scale surfaces or surfaces with Class A coatings on blast-cleaned steel)
	=	0.50 for Class B surfaces (uncoated blast-cleaned steel surfaces or surfaces with Class B coatings on blast-cleaned steel)
	=	0.35 for Class C surfaces (roughened hot-dip galvanized surfaces)
D_u	=	1.13, a multiplier that reflects the ratio of the mean installed bolt pretension to the specified minimum bolt pretension
T_m	=	Specified minimum bolt pretension (28 kips for ¾ inch A325, F1852 diameter bolts)
N_b	=	Number of bolts in the joint

It can be seen that the mean slip coefficient assumed for blast-cleaned surfaces is 0.50 and is the highest specified. The use of blast cleaned steel is recommended to achieve a high slip resistance but raises a question about the possible deterioration of the slip performance if the blast cleaned surface rusts. A small number of tests investigating the effects of rusting on this mean slip coefficient were added to this research effort by performing laboratory slip experiments on weathered and blast-cleaned samples used in the delayed tensioning series.

3. BOLT PRETENSION MEASUREMENT METHOD

The method used throughout this research for the measurement of bolt pretension was that of stretch or the elongation monitoring. The ultrasonic measurement of bolt length or elongation is related to the bolt force, and the relationship can be calibrated by direct tension testing. The bolt stiffness (load vs. elongation) can also be estimated theoretically. The ultrasonic instrument used for this method was the Bolt Gage 3 from BIDWELL Industrial Group Inc. Ultrasonic measurement provides a very precise method of determining the elongation of a bolt and has been designed to cancel the influence of stress on the material transmission of ultrasound. This elongation is nearly a constant proportion of the bolt load if the bolt remains elastic. The most important features of this approach include:

a) The realistic material response was uninfluenced by a force measurement that tends to reduce the effective stiffness of the bolted parts;
b) The technique does not require special handling or modification of the bolt that would influence the physical parameters of interest;
c) The measurement technique is portable and compensated for temperature changes.

3.1 BASIC CONCEPT: STRETCH CONTROL METHOD

Considering the bolt to be a stiff spring, the relationship between the change in length of the bolt and the preload within it can be described by:

$$\Delta L = T\left(\frac{1}{K_b}\right) \tag{3.1}$$

where,

ΔL = the change in length of the bolt

K_b = the stiffness of the bolt

T = tensile preload in the bolt

This equation presents the basic mechanisms of the stretch control of bolt tension where the bolt is modeled as a simple spring. The preload determined from above equation has the same degree of accuracy as the measurement of the change in bolt length. In this report, the change in length of the bolt was measured accurately using an ultrasonic device, the Bolt Gage. The resolution of the Bolt Gage is about one in hundred thousand of an inch (0.00001”) with stable repeatability of (0.0001”) and thus results in a preload resolution on the order of one ten thousandth of a kip for typical bolt sizes. The stiffness of the bolt is calibrated in a laboratory tension test for the assembly geometry as it was installed; the theoretical estimation of bolt stiffness is derived from simple mechanics as presented later.

3.2 BOLT GAGE MEASUREMENT TECHNIQUE

To determine the amount of stretch, the Bolt Gage instrument sends a series of sound pulses into one end of a bolt, and effectively measures the time for the echoes to return. This device is provided with a microprocessor and software that analyze the returning echo duration and compare the information to a reference value for the bolt; the Bolt Gage (Model 3) analyzes this information and displays the new bolt length and the bolt stretch, stress and load calculated according to the input parameters. Figure 3.1 is a picture of the instrument including a 3 inch reference cylinder in the foreground.

Figure 3.1 Bolt Gage 3

Before the Bolt Gage is mounted on the bolt to measure the stretch, a very important first step is the preparation of the bolt to mount the transducer. Non-parallel, uneven or rough surfaces will not work. The transducer contact area determines the amount of signal that can be coupled from the transducer to the bolt. It is better to have a very flat spot on the head of the bolt that is large enough for the transducer area to be in flat contact. The tip of the bolt must also be reasonably flat, smooth and parallel to the head surface to provide an adequate reflection of the sound pulse.

The bolt stretch measurement for the twist-off bolt begins after the installation of the bolt; it is necessary to measure the stretched length first. The stretched length is recorded on the Bolt Gage before the tension is released. With the transducer remaining on the bolt head to minimize remounting effects, the bolt is loosened with a manual, dial-indicating torque wrench and the unloaded length is measured. The change in bolt length is automatically shown on the display of the Bolt Gage after nut loosening. A higher than expected removal torque may be a cause for rejection of the measured value because inelastic behavior will lead to erroneous conclusions.

3.3 THEORETICAL ESTIMATE OF BOLT STIFFNESS

The bolt is in effect a stiff spring. From Equation (3.1), the spring constant or stiffness of the bolt is simply defined as:

$$K_b = \frac{T}{\Delta L_c} \tag{3.2}$$

Applying Hooke's law and the relationship between springs in series to Equation (3.2), Bickford (8) suggested an equation and parametric values to compute the stiffness of a bolt:

$$\frac{1}{K_b} = \frac{L_{be}}{EA_b} + \frac{L_{se}}{EA_s} \tag{3.3}$$

where,

L_{be} = effective body length (approximated as the true body length plus one-half of the thickness of the head of the bolt)

A_b = body cross-sectional area

E = Modulus of elasticity

L_{se} = effective thread length (approximated as length of exposed threads plus one-half the thickness of the nut) (in., mm)

A_s = effective cross-sectional area of threads

This effective length calculation by Bickford (1995) was made empirical with the assumptions that the average stress level in the head of the bolt is one-half the body stress, and one-half of the threads engaged by the nut are loaded at the "exposed thread" stress level. There is no simple way to study the actual stress distribution because the stress distribution depends on the geometry of the particular bolt and the fit with the nut. Bickford (1995) also pointed out that the above assumption is good for long, slender bolts, but as the length-to-diameter ratio of the bolt decreases, and the bolt becomes shorter and stubbier, the assumption may not be valid.

Based on Equation (3.3), and compared with the calibration results of bolt stiffness obtained from direct tension laboratory testing through trial and error, the following calculated effective lengths, defined in Equation 3.3, were found to be reasonable and can be used for all the round head ASTM F1852 twist off bolts tested in this report:

$$L_{se} = L_s + 0.45 \times H_n \tag{3.4}$$

$$L_{be} = L_b + 0.40 \times H_h \tag{3.5}$$

where,

L_s = length of exposed threads

H_n = thickness of the nut

L_b = body length

H_h = thickness of the head of the bolt measured from the bottom

In Equation (3.3), Bickford suggested that one half of the head height was used to compute the effective body length for hex head bolt. Before the parameter of 0.45 and 0.40 was determined, several combinations of such coefficients as 0.5, 0.45, 0.4, and 0.35 were verified in Equation (3.4) and Equation (3.5) to acquire a better interpretation of the bolt stiffness. The detailed comparisons among the various combinations of those coefficients were shown in Table 3.2. Table 3.1 shows the stiffness calculation results of 3/4 inch diameter button head ASTM F1852 twist-off bolts of three different lengths and with varying grip lengths when parameters of 0.45 and 0.40 was used in Equation (3.4) and Equation (3.5), separately. The variability between the calculated theoretical bolt stiffness K_t and the measured and calibrated bolt stiffness in direct tension K_c ranges from -2% to 1%, and average variation was about -1%. Correspondingly, with the other combinations of parameters of 0.5, 0.45, 0.4, and 0.35 as shown in Table 3.2, the average variations were about -5%, -4%, -1% and 0%, respectively. The last combination of 0.45 and 0.35 was not chosen because it may overestimate the bolt stiffness for some bolts. The assumptions of the effective lengths shown in

Equation (3.4) and Equation (3.5) were suitable for ASTM F1852 round head bolts with length-to-diameter ratio of 3 through 4.5. The theoretical bolt stiffness calculated with these assumptions can be used for the estimation of the bolt pretension in the field when using the Bolt Gage measurement method and when the direct bolt calibration is not possible.

Table 3.1 Bolt stiffness calculation

Bolt Size (1)	H_h (in.) (2)	L_b (in.) (3)	L_{be} (in.) (4)	A_b (in.) (5)	L_G (in.) (6)	L_S (in.) (7)	H_n (in.) (8)	L_{Se} (in.) (9)	A_S (in.^{2}) (10)	K_t (kips/in.) (11)	K_c (kips/in.) (12)	$\Delta K/K_c$ (%) (13)
ϕ 3/4 x 2 1/2	0.48	0.87	1.06	0.442	1.250	0.380	0.73	0.71	0.334	6634	6729	-1
ϕ 3/4 x 2 3/4	0.49	1.16	1.36	0.442	1.625	0.465	0.73	0.79	0.334	5513	5651	-2
ϕ 3/4 x 3	0.48	1.44	1.63	0.442	1.875	0.435	0.73	0.76	0.334	5019	5061	-1
ϕ 3/4 x 3 1/4	0.48	1.63	1.82	0.442	2.000	0.370	0.73	0.70	0.334	4829	4862	-1
ϕ 3/4 x 3 1/4	0.48	1.63	1.82	0.442	2.250	0.620	0.73	0.95	0.334	4310	4292	0

Note: L_b = measured unthreaded bolt body length; L_{be} = Lb + 0.40 H_h; H_h = measured bolt head height; L_S = length of exposed threads; L_{Se} = L_S + 0.45 N_h; N_h = measured nut height; L_G = grip length; K_c = average calibrated bolt stiffness in direct tension; $\Delta K/K_c$ = the variation of K_t expressed as a percentage of K_c

Table 3.2 Determination of parameters in bolt stiffness calculation

Bolt Size	grip length	calibrated stiffness	$L_{se} = L_s + 0.5\ N_h$ $L_{be} = L_b + 0.5\ H_h$		$L_{se} = L_s + 0.5\ N_h$ $L_{be} = L_b + 0.45\ H_h$		$L_{se} = L_s + 0.45\ N_h$ $L_{be} = L_b + 0.40\ H_h$		$L_{se} = L_s + 0.45\ N_h$ $L_{be} = L_b + 0.35\ H_h$	
(1)	L_G (in.) (2)	K_c (kips/in.) (3)	K_t (kips/in.) (4)	$\Delta K/K_c$ (%) (5)	K_t (kips/in.) (6)	$\Delta K/K_c$ (%) (7)	K_t (kips/in.) (8)	$\Delta K/K_c$ (%) (9)	K_t (kips/in.) (10)	$\Delta K/K_c$ (%) (11)
ϕ 3/4 x 2 1/2	1.250	6729	6329	-6	6402	-5	6634	-1	6715	0
ϕ 3/4 x 2 3/4	1.625	5651	5299	-6	5351	-5	5513	-2	5570	-1
ϕ 3/4 x 3	1.875	5061	4843	-4	4886	-3	5019	-1	5065	0
ϕ 3/4 x 3 1/4	2.000	4862	4665	-4	4705	-3	4829	-1	4871	0
ϕ 3/4 x 3 1/4	2.250	4292	4180	-3	4211	-2	4310	0	4344	1
Average				-5		-4		-1		0

Note: K_c = average calibrated bolt stiffness in direct tension; K_t = calculated theoretical bolt stiffness; $\Delta K/K_c$ = the variation of K_t expressed as a percentage of K_c

3.4 LABORATORY CALIBRATION OF BOLT STIFFNESS

To calibrate the bolt stiffness in the laboratory, the bolt was tested in the same test apparatus that was used for the direct tension testing. This direct tension test set-up is described in more detail in Chapter 4. The Bolt Gage was used to measure the elongation of the bolt at several regular load steps during the loading and unloading process. For each bolt stiffness calibration, 3 bolts were loaded and unloaded in the 220 kips load capacity MTS universal frame following the same procedure. The end preparation of the bolts was required before the bolts were inserted in the tensile testing adapter for the use of the Bolt Gage. The next very important step was to make sure that the bolt grip length was provided exactly as required. As expected, for the same bolt, the bolt stiffness decreased as the grip length of the bolt increased. This can be observed from the bolt stiffness results in Table 3.1. The bolt was loaded up to the proof load of 28 kips, and then unloaded. During the loading and unloading process, the elongation readings from the Bolt Gage and the loads from the MTS were recorded at several load steps for further analysis. Figure 3.2 on the next page, shows a typical bolt tension versus applied displacement relationship that was obtained from a full direct tension test for physical properties.

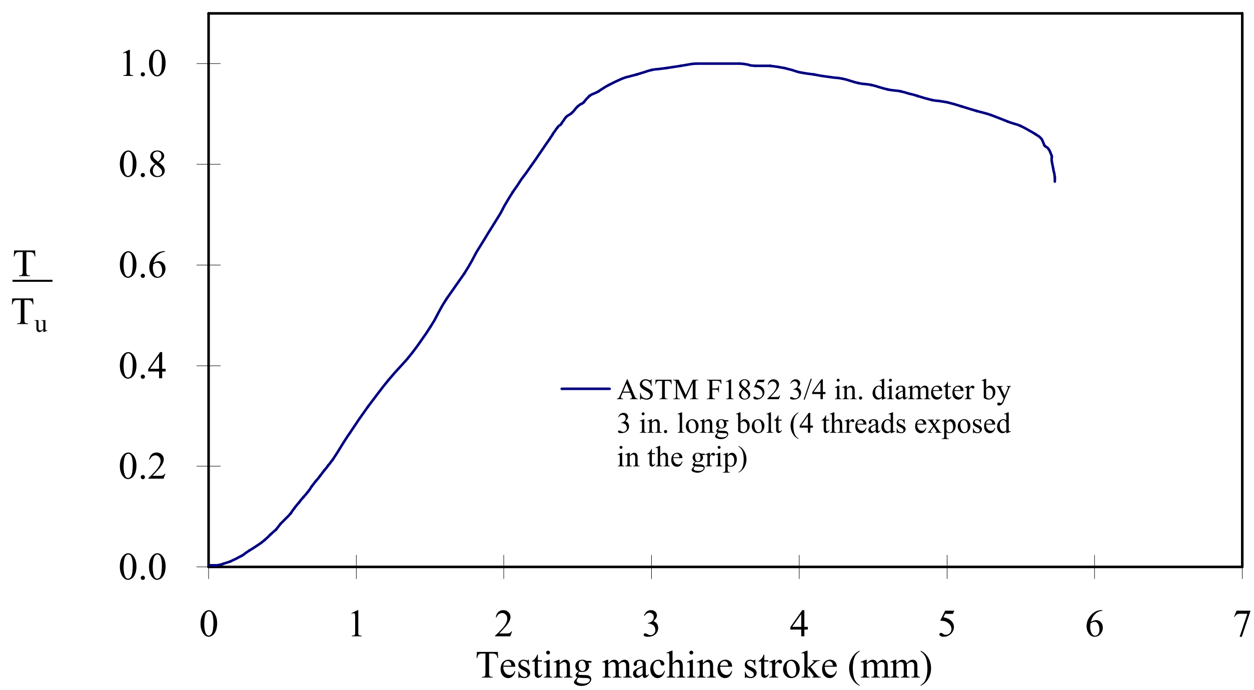


Figure 3.2 Bolt tension vs. machine stroke relationship in direct tension

The testing machine displacement is slightly larger than the actual bolt elongation but quite similar in nature. As can be seen from the curve, at the initial loading stage, the relationship of bolt tension and bolt elongation was not linear. This nonlinearity was caused by the changing boundary conditions. When the load was first applied to the bolt, perhaps only part of the threads were engaged, and the local contact stress on the parts was quite high, and some of them may have locally yielded. As the load increased, the threads were brought into full engagement, and the relationship of the bolt tension and bolt elongation became linear. Similarly, the boundary conditions were changing gradually when the bolt was unloaded. Only those test data in the linear range were used in the following data evaluation.

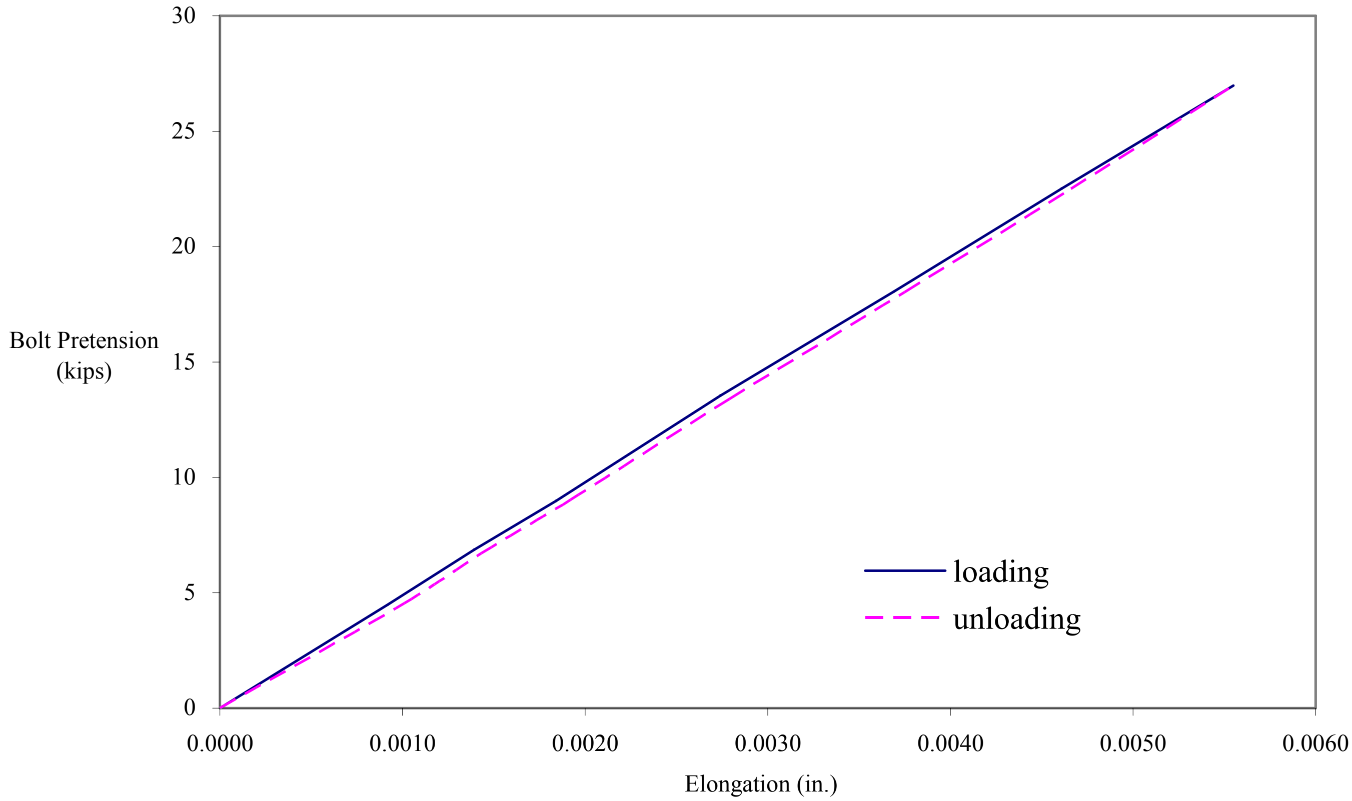


Figure 3.3 Loading vs. unloading curves for bolt stiffness calibration

The data in Figure 3.3 illustrates the loading and unloading curves for a particular bolt. The curves were drawn from the data recorded in a calibration test. Although a slight difference was observed between the loading and unloading path, the unloading curve returned to the origin indicating essentially an elastic . To determine the bolt stiffness, linear regression analyses were performed on the data that was obtained during the loading and unloading process. Because of the nonlinearity at the lower load level, the data under about 10% of the ultimate tensile strength (5 kips) were not included in the regression analysis. The results of regression analysis showed that the linear regressions were able to represent both loading and unloading curves very accurately. The bolt stiffness obtained from the loading path was slightly different than that from the unloading path, and it also varied a small amount from bolt to bolt. The Y-intercepts were not zero because of the nonlinearity found at the lower load stage. There was not a regular and consistent Y-intercept derived from the linear regression analyses. They ranged from small positive values to small negative values depending on the loading direction (loading or unloading).

To calibrate the pretension in the TC bolts, the change in length measurement was taken after the loosening of the nut, that is, after the releasing of the load in the bolt. Thus, it could be more appropriate for this application to use the data obtained in the unloading process to determine the bolt stiffness. Further, it may be even more reliable to calculate the preload in the specific bolt with the Equation (3.6) below, but it was not easy to determine a Y constant for general use.

$$T = K_u \times \Delta L + Y \tag{3.6}$$

where,

K_u = bolt stiffness obtained from linear regression analysis of unloading data

Y = the Y-intercept obtained from the linear regression analysis of unloading data

ΔL = the change in bolt length

Several bolts per group were calibrated during the loading and unloading processes, each resulting in slightly different slopes and Y-intercepts. Several analyses were performed to compare the results of the best fit approximation. First, the linear regression analyses were performed on the loading and the unloading data for the individual bolts separately. It was found that the Y-intercepts derived from the loading processes were algebraically greater than those from the unloading processes in general, and the Y-intercepts derived from the unloading paths were generally negative. Secondly, the data obtained in the loading and the unloading process for all the calibrated bolts were grouped together separately to obtain the average stiffness and Y-intercept from the linear regression analysis. It was then found out that for each tested bolt lot the average slope of the unloading path was stiffer than that of the loading path, and the average Y-intercept derived from the unloading path was algebraically smaller than that from the loading path. Table 3.3 shows the laboratory calibration results of bolt stiffness and the corresponding Y-intercept for each tested bolt lot. The average stiffness and Y-intercept calculated from the combined unloading data in the same load range for each bolt lot were taken as the definitive calibration.

As shown in Table 3.3, the Y-intercepts derived from the regression analysis of the combined unloading data for all the tested bolt lots were very small. Further, if the best fit line was forced through the origin during the regression analysis, then the bolt pretension should be calculated by the corresponding equation:

$$T = K_u^o \times \Delta L \qquad (3.7)$$

where,

K_u^o = average bolt stiffness obtained from linear regression analysis of combined unloading data with the best fit line being forced through the origin

ΔL = the change in bolt length

It was observed that for a typical bolt elongation range of 0.0040 in. to 0.0070 in. the error between bolt pretensions calculated through Equation (3.6) and Equation (3.7) was only about 0 to 0.3 kips. The detailed comparison between Equation (3.6) and Equation (3.7) was shown in Table 3.4. The error of 0.3 kips can be neglected. This error is in the order of the resolution of the Bolt Gage of 0.0001 inch. Corresponding to the typical bolt stiffness of around 5000 kips/in., the tolerance of bolt pretension is about 0.5 kips for the sizes of bolt assemblies that were tested and reported herein. Thus, Equation (3.7) was used to evaluate the pretensions achieved in ASTM F1852 TC bolts.

Table 3.3 Bolt stiffness laboratory calibration results

Bolt lot #	Bolt #	Loading			Unloading		
		K, Stiffness (kips/in.)	Y-intercept (kips)	R square	K, Stiffness (kips/in.)	Y-intercept (kips)	R square
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
A	1	4785	0.4	1.000	4966	-0.4	0.999
	2	4781	0.3	1.000	4885	-0.2	1.000
	3	4883	0.4	1.000	4996	-0.5	1.000
	combined data	4799	0.4	0.999	**4948**	**-0.3**	1.000
B	1	5185	-0.4	1.000	5189	-0.4	1.000
	2	5106	0.1	1.000	5189	-0.5	1.000
	3	5166	-0.3	1.000	5160	-0.3	1.000
	combined data	5146	-0.2	1.000	**5161**	**-0.4**	1.000
C	1	5761	0.0	0.999	5761	-0.3	0.999
	2	5415	0.9	1.000	5621	0.0	1.000
	3	5621	0.6	1.000	5761	-0.3	0.999
	combined data	5589	0.5	0.999	**5712**	**-0.2**	0.999
D	1	5685	-0.1	0.999	5621	0.0	1.000
	2	5621	0.6	1.000	5671	-0.3	0.999
	3	5621	0.0	1.000	5685	-0.3	0.999
	combined data	5633	0.2	0.998	**5686**	**-0.2**	0.999

Table 3.4 Comparison between bolt pretension calculation results with two methods

Bolt lot #	Elongation (in.)	**$T = K_u (\Delta L) + Y$**				**$T = K_u^o (\Delta L)$**		
		K_u, Stiffness (kips/in.)	Y-intercept (kips)	R square	T, Tension (kips)	K_u^o, Stiffness (kips/in.)	R square	T, Tension (kips)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
A	0.0045	**4948**	**-0.3**	1.000	21.9	**4862**	0.999	21.9
	0.0070				34.3			34.0
B	0.0045	**5161**	**-0.4**	1.000	22.8	**5061**	0.999	22.8
	0.0070				35.7			35.4
C	0.0040	**5712**	**-0.2**	0.999	22.6	**5651**	0.999	22.6
	0.0065				36.9			36.7
D	0.0040	**5686**	**-0.2**	0.999	22.5	**5628**	0.999	22.5
	0.0065				36.7			36.6

4. EXPERIMENTAL PROGRAM

For pretensioned and slip-critical joints, the bolt pretension must meet or exceed the specified minimum bolt pretension requirements of the RCSC Specification. The pretension of twist-off tension control bolts after installation is the main concern of this report; particularly the ability to delay the final installation and achieve an adequate pretension is a principal focus. Past laboratory research on high strength bolting in general and on TC bolts showed that the tensile performance of a fastener strongly reflects the condition of friction that exists on the threads, and for TC bolts the condition of the nut to washer interface further affects the tension at twist-off. In examining the delayed installation various parameters that influence the achieved pretension are studied in light of the current RCSC Specification (2004) and the research effort thus attempts to examine potential solutions for problems that are encountered in the test results.

In the field, the twist-off tension control bolt assemblies are usually inserted in the joints and tightened manually to a snug-tight condition and then are installed with an automatic TC wrench a few hours, days or weeks later. During this period, the lubricated condition of the threads and washers of the twist-off tension control bolt assemblies has been shown to change; the “lubricating condition” may be related not only to the surface condition of the part but may also refer to the condition of the substance applied specifically as lubrication. The question is: Does the minimum required bolt pretension develop according to the RCSC Specification if tensioning is delayed after installation of the bolt in the structure?

The authors are not aware of any available test data on pretensions of twist-off tension control bolts in the field; technical difficulties in measuring the bolt tension easily has been the main in situ drawback. The more recent technique of using an ultrasonic measurement device, Bolt Gage, to obtain the bolt tension has been successfully used in the field on high-strength bolts (Kulak and Obaia, 1992, Kulak and Birkemoe, 1993). The technique is used for twist-off tension control bolts in this laboratory/field investigation. Laboratory research has established the feasibility of using the Bolt Gage to obtain the bolt tension in twist-off tension control bolts in the lab or in the field.

The F1852 twist-off bolt assemblies examined in this report were supplied by four North American bolt producers/suppliers with one nominal diameter of ¾ in. and popular lengths of 2 ¾, 3 and 3 ¼ inches (not including the spline). To compare the twist-off bolt assembly installation with the turn-of-nut technique, the bolt lengths were chosen with the consideration of the turn-of-nut installation method for reinstallation; the turns requirement from snug is different for bolt lengths up to and including 4 diameters versus those exceeding 4 diameters in length. Table 4.1 shows the information of these bolt lots. It should be noted that manufacturer A provided two separate lots of fasteners of the same size but at different times.

Table 4.1 Bolt lot information

Company (1)	Bolt size (in.) (2)	Bolt Assembly (3)	Quantity (4)	Packing Date (5)
A (lot 1)	ϕ 3/4 -10 UNC x 3 1/4	F1852-1SL + A563-DH + F436-1	210	June, 2002
A (lot 2)	ϕ 3/4 -10 UNC x 3 1/4	F1852-1SL + A563-DH + F436-1	3 x 210	June, 2004
B	ϕ 3/4 -10 UNC x 3	F1852-1SL + A563-DH + F436-1	160	Aug. 2003
C	ϕ 3/4 -10 UNC x 2 3/4	F1852-1SL + A563-DH + F436-1	105	Mar. 2004
D	ϕ 3/4 -10 UNC x 2 3/4	F1852-1SL + A563-DH + F436-1	105	Mar. 2004

4.1 BOLT GEOMETRICAL AND MECHANICAL PROPERTIES

Bolt/nut/washer dimensional and physical mechanical properties are the main factors affecting the control of pretension in the twist-off tension control bolts. The F1852 twist-off bolt is a special-geometry bolt with an extended spline tip. This enables the installation of twist-off bolts with a special electrically-powered double chuck wrench. The torque requirements of the bolts are achieved by engaging the bolt spline tip and nut with inner and outer chuck of the wrench, and driving this wrench until the spline tip shears off at the breakneck (reduced size of the cross section as shown 4.1). The size of the spline tip should satisfy the requirements on the ASTM F1852 (ASTM, 2004) to engage the installation wrench appropriately. The breakneck diameter is of importance, because the spline tip shears off at this notch when the required torque is achieved. The size of the bolt head must also meet the minimum requirements specified in the ASTM F1852. A recent report on the effects of head size on the performance of twist-off bolts (Schnupp et al., 2003) pointed out that as the amount of bearing surface under the twist-off bolt head does not affect the achieved bolt pretension, the minimum bearing surface diameter of the bolt head required in the ASTM F1852 specification is adequate for reliable bolt performance even in oversized or slotted holes.

The mechanical properties for a bolt lot were provided in the form of a certificate by the manufacturer/supplier but were further tested to confirm that the twist-off bolts satisfied the strength and hardness requirements of ASTM A325. The bolts with higher material strength and hardness would be expected to achieve higher pretensions if the geometry and surface treatments are identical and if the splined end can be twisted off as limit on torque.

4.1.1 Bolt Geometrical Properties

According to the requirements of ASTM F1852-00 (ASTM, 2000) on the dimensions for twist-off structural bolt, several measurements were taken on the bolts with micrometer calipers. Three bolts from each lot were measured. The measured dimensions of the bolt were the height of the head, the bearing surface diameter, the length of the spline, the width across flats of the spline, the diameter of the breakneck, as well as the unthreaded body length. The average dimensions and standard deviations for bolts from the four manufacturers are listed in Table 4.2. The dimensions of the twist-off bolts from all manufacturers met the ASTM F1852 requirements. Although there is no specific requirement on the diameter of the reduced section, D_n (Figure 4.1), between the bolt end and the spline in the ASTM F1852 specification, the diameters of the reduced section were also measured for comparison. The results showed that there was little difference among the reduced diameters for these sizes of bolts and for the lots tested. The unthreaded body length determination was required for the calculation of an estimate of the bolt stiffness.

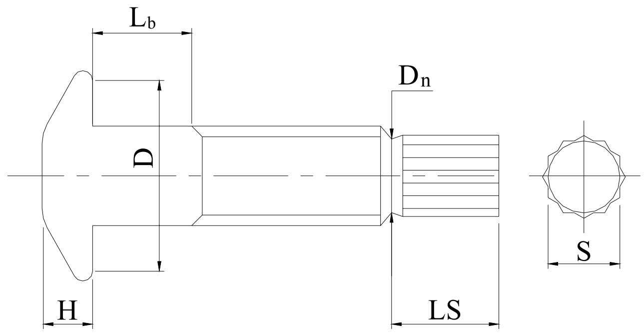


Figure 4.1 Bolt Dimensions

Table 4.2 Dimensions of TC bolts

Company	D		H		LS		S		D_n		L_b	
	Bearing Surface Diameter (in.)		Head Height (in.)		Length of Spline (in.)		Width across Flats (in.)		Reduced Diameter (in.)		Unthreaded Length (in.)	
	Avg.	STD	Avg.	STD	Avg.	STd	Avg.	STD	Avg.	STD	Avg.	STD
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
A	1.49	0.01	0.479	0.001	0.61	0.001	0.52	0.00	0.539	0.003	1.625	0.004
B	1.48	0.01	0.483	0.001	0.64	0.004	0.53	0.00	0.539	0.002	1.439	0.004
C	1.52	0.01	0.485	0.006	0.65	0.002	0.53	0.00	0.535	0.001	1.155	0.008
D	1.41	0.01	0.490	0.005	0.65	0.002	0.52	0.00	0.536	0.002	1.150	0.005

Note: The corresponding dimensions on the bolt are shown in Figure 4.1; three bolts were measured from each manufacturer

4.1.2 Bolt Mechanical Properties

Mechanical property requirements for twist-off tension control bolts include the hardness and the tensile strength properties. Both tests were conducted in conformity with the standard test methods specified in ASTM F606-00.

The Rockwell C Hardness Scale was used for the bolt hardness test. Three bolts from each lot were tested on the hardness. For each bolt, four (4) readings were taken from the test location, and three

(3) readings were from the bolt shank. Figure 4.2 indicates the locations of the detailed hardness tests. Figure 4.3 illustrates photographically the apparatus use for the Rockwell C hardness test in the lab.

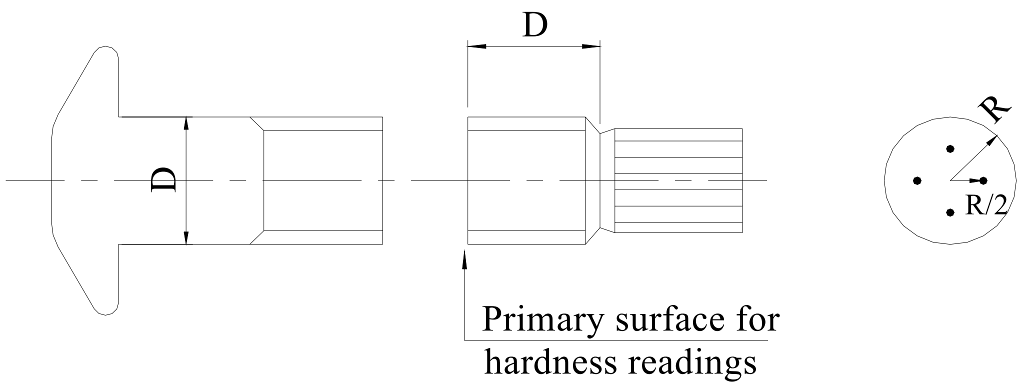


Figure 4.2 Hardness readings test locations

Axial tension tests of full-size bolt assemblies were conducted to measure the ultimate tensile strength of the bolt; indirectly the nuts were also given a proof test. Three (3) bolts from each lot were axially loaded to failure. The bolts were mounted on a tensile bolt loading device (see Figure 4.4) with four complete threads exposed in the grip length. This was obtained by freely running the nut to the thread runout of the bolt and then unscrewing the nut four full turns. The tensile testing adapter included three parts: the upper and lower components with six evenly spaced 1 in. diameter "pusher" rods, and two identical plates connected by the bolt specimen assembly. Each middle plate has six corresponding holes to engage those "pusher" rods as well as a center hole with the appropriate size for the bolt tested. The bolt assembly was inserted in the center holes of the two plates and the nut was adjusted to the correct grip length. The outer holes of these two plates are staggered so that the rods can pass through one plate and push on the others. This assembled tensile testing adapter was centered on the loading platform of an MTS100 ton universal testing machine and then loaded in compression; the bolt positioned in the center of the adapter was subjected to axial tension with the top adapter pushing downward on the bottom plate and the bottom adapter pushing upward on the top plate.

Figure 4.3 Illustration of the Rockwell hardness test

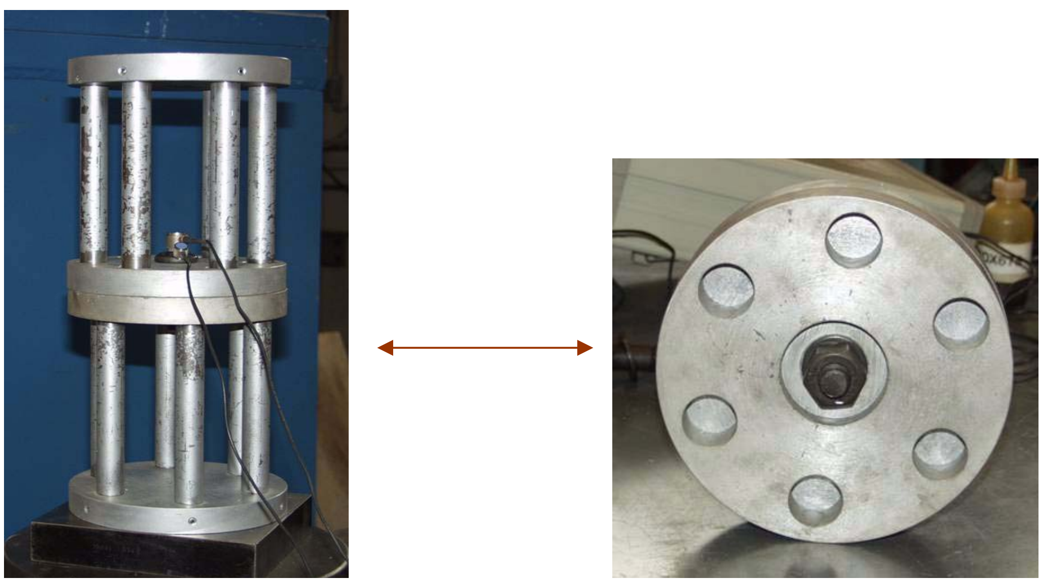


Figure 4.4 Tensile bolt testing adapter

The information of bolt mechanical properties provided by the manufacturer and test results from the laboratory are reported in Table 4.3. The laboratory results showed that bolts from the four manufacturers met the ASTM mechanical property requirement.

Table 4.3 Bolt mechanical properties

Arbitrary Company Designation/ Lot (1)	Bolt size (in.) (2)	Information from Manufacturer			Results from laboratory			
		Hardness (RC25-34) (3)	Proof Load (28.4 kips) (4)	Tensile Strength (kips) (5)	Hardness (RC25-34) Average (7)	Hardness (RC25-34) STD (8)	Direct Tensile Strength Average (kips) (9)	Direct Tensile Strength STD (kips) (10)
A (lot 1)	ϕ 3/4 x 3 1/4	28.3	All Pass	47.2	28.1	0.7	48.2	0.4
A (lot 2)	ϕ 3/4 x 3 1/4	29.5	All Pass	50.9	29.7	0.6	51.0	0.2
B	ϕ 3/4 x 3	31.6	All Pass	50.3	31.3	0.1	52.8	0.1
C	ϕ 3/4 x 2 3/4	32.3	All Pass	51.1	31.7	0.8	51.8	0.9
D	ϕ 3/4 x 2 3/4	31.4	All Pass	49.9	32.8	0.5	51.9	0.5

Another series of axial tension tests were performed on bolts from manufacturer A to investigate the effect of the grip length (number of threads on bolt tensile strength and the bolt stiffness. Two (2) bolts per group were mounted in the tensile testing adapter with 2, 4 and 6 threads exposed between the grip separately and were loaded up to failure using the MTS machine. The number of threads exposed in the grip was determined in the same manner as described above. Meanwhile, the Bolt Gage was also applied to measure the elongation of bolts at several load steps during the axial tension loading. The transducer of the Bolt Gage was always removed from the bolt head before the bolt was loaded up to failure by fracture. The test results are presented in Table 4.4 and Figure 4.5.

It was observed as expected that the measured ultimate tension of bolt decreased as the number of threads exposed between the grip increased. According to ASTM F606, the average measured ultimate tension of bolt with 4 threads exposed between the grip was taken as the measured bolt tensile strength. Note also from Figure 4.5 that the bolt stiffness decreased as the grip length increased; from 2 to 6 threads the stiffness decreased by approximately 18 percent.

Table 4.4 Direct tension test results for bolts with variable grip length

Load Point	**Load**		**Elongation (in.)**					
	(kN)	(kips)	*2 threads exposed*		*4 threads exposed*		*6 threads exposed*	
			Bolt #1	#2	#3	#4	#5	#6
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	0	0.0	0	0	0	0	0	0
2	5	1.1	0.0002	0.0003	0.0002	0.0002	0.0004	0.0003
3	10	2.2	0.0004	0.0005	0.0005	0.0004	0.0006	0.0005
4	25	5.6	0.0011	0.0012	0.0012	0.0012	0.0014	0.0013
5	50	11.2	0.0022	0.0023	0.0024	0.0023	0.0027	0.0026
6	100	22.5	0.0043	0.0044	0.0047	0.0046	0.0053	0.0051
7	125	28.1	0.0054	0.0055	0.0060	0.0057	0.0066	0.0065
8	150	33.7	0.0066	0.0067	0.0073	0.0070	0.0080	0.0078
9	175	39.3	0.0072	0.0073	0.0080	0.0077	0.0088	0.0086
10	180	40.5	0.0082	0.0081	0.0092	0.0088	0.0100	0.0099
F_u (kips)			50.0	50.3	48.2	48.3	47.0	47.0
F_u / F_m			1.25	1.25	1.20	1.20	1.17	1.17

Note: F_u = measured ultimate bolt tensile strength; F_m = specified minimum tensile strength (40.1 kips)

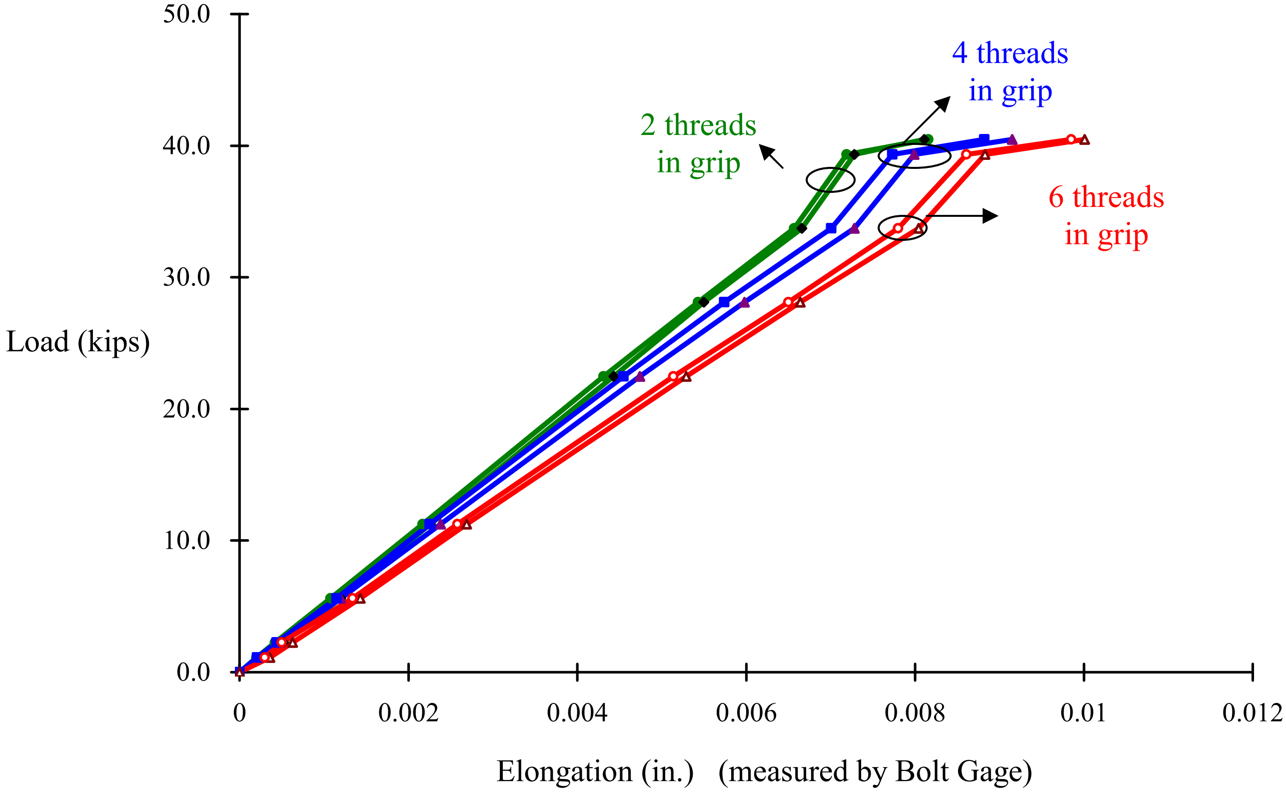


Figure 4.5 Tension vs. Elongation (direct tension test)

4.2 INSTALLATION OF ASSEMBLIES WITH VARIABLE THREAD/WASHER CONDITIONS

According to Kulak and Undershute's report (1994), the frictional conditions of threads and nut/washer interface are the key issues that influence the twist-off bolt pretension, and the installed pretension tend to decrease as the coefficient of the friction between the bolt and nut threads and/or that at the nut-washer interface increases. To create an elevated level of friction and then examine the twist-off bolt performance, the bolts were treated in several attempts to eliminate or obscure the lubricant or its performance. The Bolt Gage technique was used to establish the bolt pretension that was achieved.

These preliminary or trial tests were performed on a small number of bolts to help design the test method and to qualify the test specimen to be used for the delayed installation testing and to establish detailed test parameters and procedure. Initial comparisons of the calibrated bolt tensions using the Bolt Gage and the installed tensions indicated on the Skidmore, for the same parameters, were also made.

4.2.1 Various Treatments to TC Bolt Assemblies

Bolt assemblies with 3/4 in. diameter by 3 ¼ in. long bolts from company A were tested in four categories. For each test category, three (3) bolts were installed in the Skidmore-Wilhelm calibrator for verification and there (3) bolts were installed in the prototype 3-plate joint. The categories were:

1. As-received bolts (6 bolts)
2. Bolt assemblies soaked disassembled in warm solution of Tide brand detergent for a few hours, scrubbed with a nylon bristle brush thoroughly in the soap water to clean off any lubricant on the washer and threads of the bolt and nut, and dried in air without additional water rinsing (6 bolts)
3. Bolts soaked in white rice vinegar for a few hours, scrubbed with a nylon bristle brush thoroughly in the white vinegar to clean off the lubricant on the washer and threads of the bolt and nut, and dried in air without additional water rinsing (6 bolts)
4. Bolts soaked in a strong solution of tri-sodium phosphate (“TSP” is a popular strong detergent) for a few hours, scrubbed with a nylon bristle brush thoroughly in the solution, and dried naturally without additional water rinsing (6 bolts).

4.2.2 Test Specimen and Test Apparatus

All bolts were installed in a 3-plate prototype joint, seen in Figure 4.6. This prototype 3-plate joint with 3 bolt holes was modified to a similar joint with four (4) bolt holes for subsequent tests. All the edges of the plates were sawn or flame cut. The holes were drilled holes, and the size and placement of the hole satisfied the requirements of CAN/CSA-S16.1-94. All the individual plates in a joint are identical and fabricated from steel meeting CSA G40.21-M300W.

Figure 4.6 Picture of prototype 3-plate joint

The Bolt Gage was used to measure the bolt tension. Skidmore-Wilhelm model MS bolt tension calibrator was also used to measure the bolt load for direct comparison and verification. The MS model of the Skidmore provides a grip length as small as 1 1/4 in. for 3/4 in. diameter bolts. The grip length of bolts tested in the 3-plate joints was 3(3/4) + 1/8 = 2 3/8 in. including the washer. The front plate of the Skidmore was replaced by a specially machined thicker plate to reach the required grip length of bolt.

4.2.3 Test Procedure for Assemblies with Variable Thread/Washer Conditions

Before the bolts were tested in the steel joint, pre-installation verifications in the Skidmore-Wilhelm bolt tension calibrator were performed. Three bolts from each test category were snug-tightened in the Skidmore with the same grip length as in the steel joint to about 5~10 kips using a spud wrench and then installed with the special electrically-powered TC bolt installation wrench (automatic TC wrench).

In the 3-plate steel joint, the bolts were first tightened to snug-tight condition with the operator's full effort using a spud wrench. The automatic TC wrench was then used to complete the tightening. Both the snug-tightening and the bolt end twist-off procedure commenced with the center bolt. After installation of the whole joint within the requirements and procedures previously described in Section 3.2, the Bolt Gage was used to measure the elongations of the bolts as they were removed.

To compare the Bolt Gage measurement results with the tensions from the Skidmore, the bolt was retensioned in the Skidmore using a torque wrench. The Bolt Gage was also employed to read the elongation. When the elongation reading shown on the Bolt Gage reached the same value as recorded previously, the tightening stopped and the tension shown on the Skidmore was recorded after any effect of friction of the pointer had been removed by a few taps on the meter. Then the bolt was loosened and the bolt elongation was monitored to ensure that it went back to zero.

4.2.4 Pretension Results and Test Observations for Various Levels of Lubricant Removal

The tension results from Skidmore verification of as-received and treated assemblies are shown in Table 4.5.

Table 4.5 Average tension results from Skidmore pre-installation verification for various bolt assembly friction conditions

Test Category (1)	Bolt # (2)	T_s (kips) (3)	T_s / T_m (4)	T_s / T_m Average (5)	T_s / T_m STDEV (6)
As-received	1	32.0	1.14	1.11	0.03
	2	31.0	1.11		
	3	30.5	1.09		
soapy water	1	28.5	1.02	1.06	0.06
	2	31.5	1.13		
	3	29.0	1.04		
white vinegar	1	24.5	0.88	0.86	0.05
	2	25.0	0.89		
	3	22.5	0.80		
TSP	1	31.5	1.13	1.10	0.04
	2	29.5	1.05		
	3	31.0	1.11		

Note: T_s = tension from Skidmore; T_m = specified minimum pretension (28 kips)

The installed tension results of bolts in the steel joints and the corresponding equi-elongation tension results from the Skidmore are shown in Table 4.6. These data are displayed graphically in Figure 4.7.

Table 4.6 Tension results for various thread and washer friction conditions

Test Category (1)	Bolt # (2)	ΔL (in.) (4)	$T_c = K_u^0(\Delta L)$ (kips) (5)	T_c / T_m (7)	T_c / T_m Average (8)	T_c / T_m STDEV (9)	T_s (kips) (10)	T_s / T_m (11)	T_s / T_m Average (12)	T_s / T_m STDEV (13)
1 as-received	1	-0.0076	30.3	1.08	1.08	0.01	32.0	1.14	1.11	0.03
	2	-0.0076	30.3	1.08			31.0	1.11		
	3	-0.0075	29.9	1.07			30.5	1.09		
2 soapy water	1	-0.0073	29.1	1.04	1.00	0.04	28.5	1.02	1.06	0.06
	2	-0.0067	26.7	0.96			31.5	1.13		
	3	-0.0070	27.9	1.00			29.0	1.04		
3 white vinegar	1	-0.0053	21.2	0.76	0.67	0.07	24.5	0.88	0.86	0.05
	2	-0.0044	17.6	0.63			25.0	0.89		
	3	-0.0045	18.0	0.64			22.5	0.80		
4 TSP	1	-0.0073	29.1	1.04	1.04	0.02	31.5	1.13	1.10	0.04
	2	-0.0071	28.3	1.01			29.5	1.05		
	3	-0.0074	29.5	1.06			31.0	1.11		

Note: ΔL = change in bolt length during nut loosening; T_c = calibrated tension; K_u^0 = calibrated bolt stiffness from direct tension test (3992 kips/in.); T_s = tension from Skidmore; T_m = specified minimum pretension (28 kips)

For each test category, the average bolt pretension from the Skidmore pre-installation verification was higher than that achieved in the steel joints. The required pretension as stipulated in RCSC Specification (2004) for pre-installation verification of TC bolt is 1.05 times the specified minimum pretension. The bolts that were treated with the white rice vinegar and the soapy water failed the pre-installation verification in the Skidmore according to the requirement in RCSC Specification.

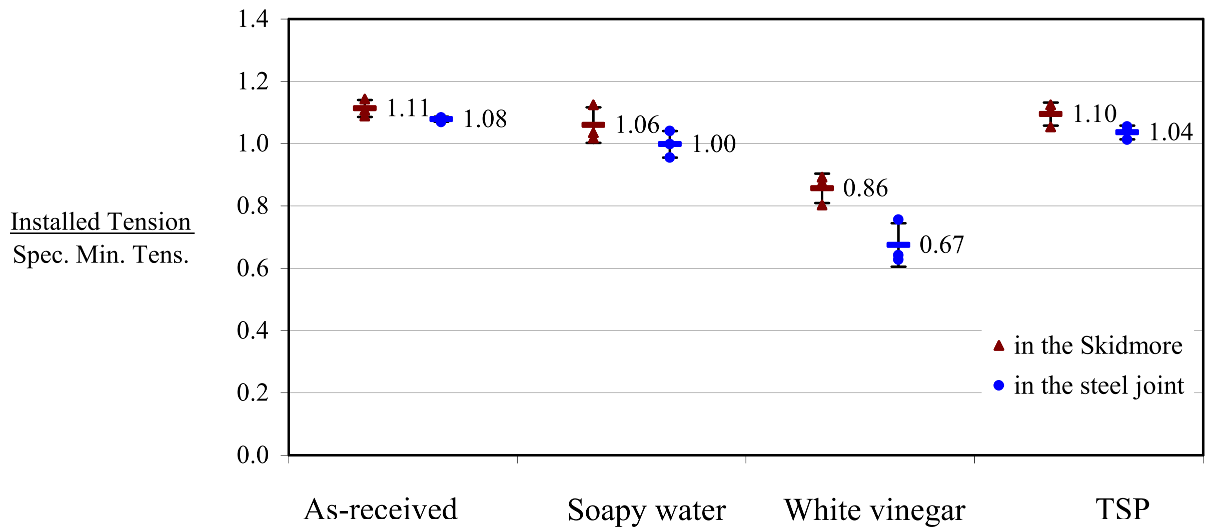


Figure 4.7 Installed tension / specified minimum tension for various bolt friction conditions

For bolts in the steel joints, the worst case for the bolt pretension also occurred in the third test category: white rice vinegar treatment. The pretensions obtained in the bolts after being treated with the white rice vinegar were much lower than the specified minimum pretension required by the RCSC Specification. It was also observed that after white vinegar treatment the color of the whole bolt assembly changed from dark black to a rusty color, as shown in Figure 4.8, and some of the threads on the bolt and nut were rusted severely. However, the most visible rusting took place when the assemblies were washed in the warm soapy water, and those subsequent bolt pretensions were near the specified minimum pretension of 28 kips. For the bolt assemblies washed in the solution of Tri-Sodium Phosphate, the threads on the bolt and nut also rusted after air drying, but the rusting condition was not as severe as that resulting from the treatment in the warm solution of Tide detergent. Correspondingly, the bolt pretensions for the TSP washed assemblies were above the minimum specified by 4%. For comparison, the pretensions of the as-received bolts exceeded 28 kips by about 8%; These “as-received” assemblies had been stored in a covered but unsealed metal keg indoors in the lab for about 4 months before the tests were performed. According to the Alberta report (1994), the preloads of these bolts may have been higher if the bolts had been tested in the earlier “as-received” condition when the container was first unsealed.

Figure 4.8 Comparison of untreated bolt (left) and bolt washed in white vinegar (right)

It can be seen in Table 4.6 that these preliminary pretensions achieved by tightening the bolts in the Skidmore to the same amount of elongation as in the steel joint were higher than those measured from the Bolt Gage by 3% on average. This variation was likely related to the change of the bolt stiffness and would have been smaller if the grip length of the bolt in the Skidmore had been equal to that in the steel joint.

4.3 DEMONSTRATION PILOT TEST FOR FIELD MEASUREMENT

As described above, a series of tests using the Bolt Gage technique were done on the 3-plate joints. To demonstrate the feasibility of the Bolt Gage pretension measurement method in the field, some tests were conducted on the connection of University of Toronto Teaching Design Aid Structure in the Galbraith Building Courtyard. The Teaching Design Aid structure was built in 1993, and all of the bolts were manually painted black to prevent rusting. Some of the twist-off bolts on the connection were just snug-tightened and left uninstalled so the frictional conditions of these bolts was likely the worst at 12 year exposure among all the delayed installation tests performed in this report. In addition, some new ASTM F1852 3/4 in. diameter by 3 1/4 in. long bolts were installed in the connection for additional testing and demonstration after the original ones were tested. These 3 1/4 in. long bolts were also first snug-tightened in the connection and then installed after several exposure periods to examine the effect of delayed installation on the achieved bolt pretension.

4.3.1 Test Specimen Description

At the first phase of this test programme, the target bolts were those twist-off bolts installed or snug-tightened on the Teaching Design Aid Structure in the Galbraith Garden. There were 34, 3/4 in. diameter by 2 1/2 in. long, ASTM F1852 twist off bolts on one of the connections of the structure. Four of these bolts were only snug-tightened. All the twist-off bolts in this connection had the same grip length of about 1 1/4 in., and they were painted black after tightening. Figure 4.9 is a photograph of the connection and Figure 4.10 displays its dimensions. Galvanized plates were used in the connection.

Since the newer group of ASTM F1852 fasteners were longer (3 1/4 in.) plate spacers of 1 in. thickness were added to make up an appropriate grip length of about 2 1/4 in. for these bolts.

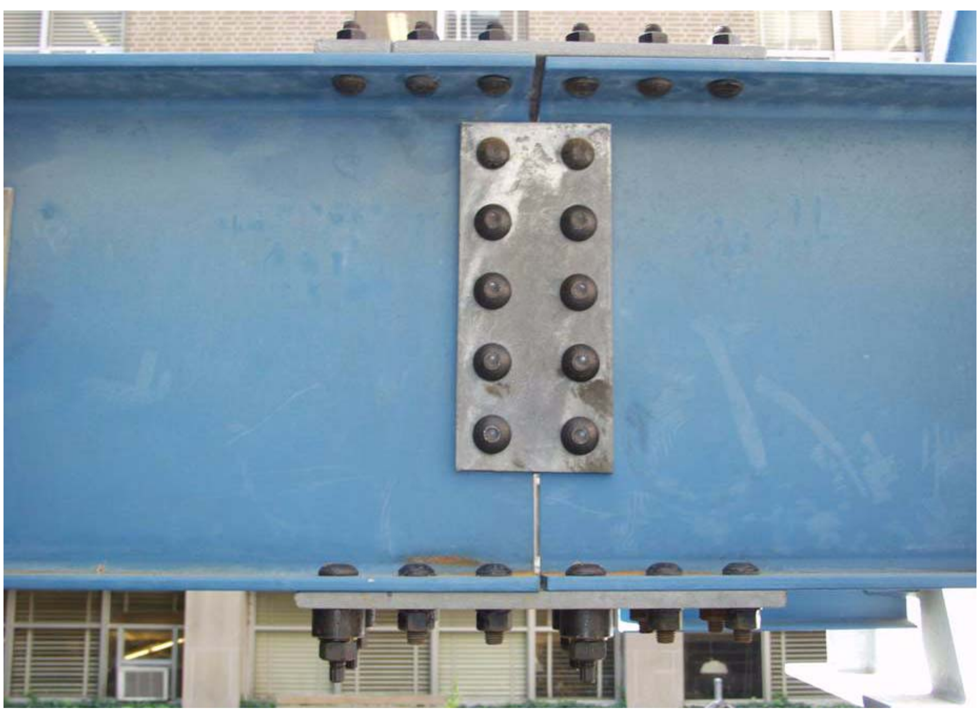


Figure 4.9 Picture of the connection on University of Toronto Teaching Design Aid Structure

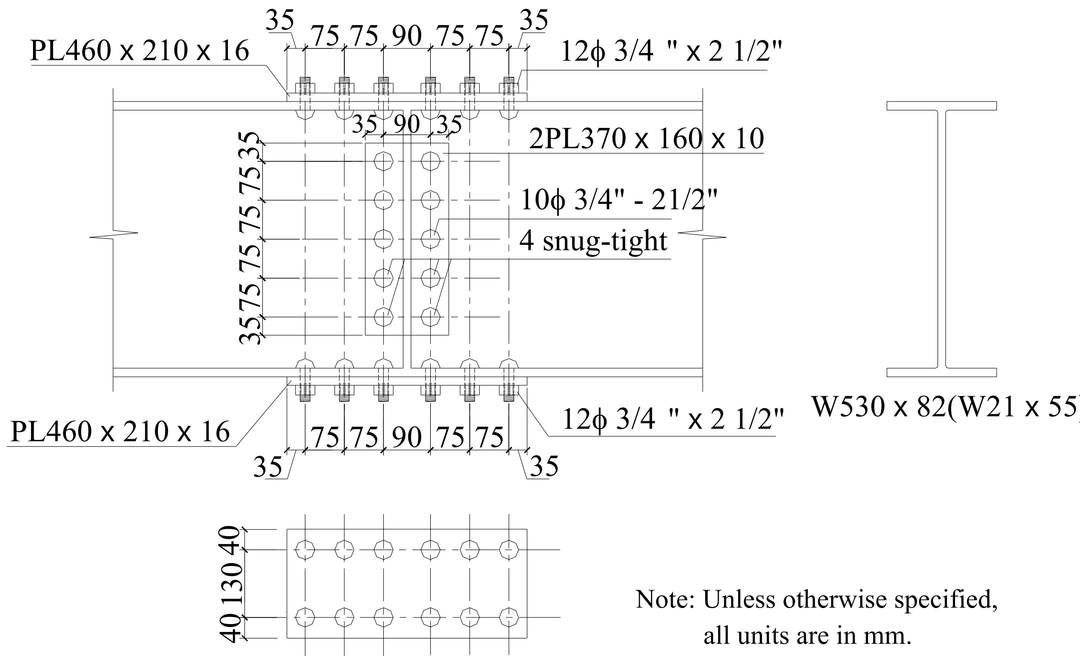


Figure 4.10 Detail of the TC bolt connection,
University of Toronto Teaching Design Aid Structure

4.3.2 Pilot Test Category

Three groups of bolts were tested on the connection on the Teaching Design Aid Structure:

1. Originally installed 3/4 in. diameter by 2 1/2 in. long bolts (8 bolts, 4 on the web, and 4 on the bottom flange).
2. Originally snug-tightened 3/4 in. diameter by 2 1/2 in. long bolts (4 bolts on the web).
3. 3/4 in. diameter by 3 1/4 in. long bolts tested under the following conditions:
    i. As-received bolts (4 bolts).
    ii. Bolts with full exposure to the weather for two weeks (4 bolts).
    iii. Bolts with full exposure to the weather for four weeks (4 bolts).
    iv. Bolts with full exposure to the weather for eight weeks (4 bolts).
    v. Wet bolts (4 bolts).

4.3.3 Test Procedure for demonstration pilot test for field measurement

For the previously installed 2 1/2 in. long bolts, the fasteners were first machined to accommodate the Bolt Gage transducer and measure the elongation of bolt during the nut loosening. The bolts were loosened manually using a regular torque wrench with a multiplier and the releasing torque was recorded. The painted condition after installation 12 years prior left a great uncertainty about the release torque.

The originally snug-tightened 2 1/2 in. long bolts, were tightened with the automatic TC wrench in a single continuous operation. Before tightening, a match-mark was drawn on the nut and protruding end of the bolt in the snug-tight condition. The turn of the nut relative to the bolt shank from snug-tight was indicated by the match-marks after the installation. After end preparation of the bolt tips, the Bolt Gage was used to measure length change during loosening. The nut was loosened with a regular torque wrench with a multiplier, and the peak releasing torque was recorded.

After the previously tested 2 1/2 in. long bolts were taken off the connection, they were replaced by the bolts of size 3/4 in. diameter by 3 1/4 in. long. To ensure an appropriate grip length a plate spacer was added for each bolt. The bolts were first snug-tightened in holes of the connection. In this test category the bolts were tested in several conditions. As-received bolts were installed right after they were snug-tightened in the holes. Bolts exposed for different periods were installed after the exposure period was reached. Wet bolts were inserted in the bolt holes after they were immersed in tap water; they were then snug-tightened and installed. In each test condition, the procedures were repeated.

4.3.4 Pretension Results of Bolts Installed in a Structural Connection

As shown in Table 4.7, the average ratios of the achieved pretension to the Specified Minimum Pretension (28 kips) were 0.75 for the originally installed bolts and 0.68 for those only snug-tightened 2 1/2 in. long bolt assemblies. Since the exposure period of these bolts was over 10 years and they had been painted after tightening, the bolt pretensions were expected to be low and not of practical value. In addition, the relaxation of bolt pretension was expected to be higher because of the six galvanized plate surfaces in the connection.

Table 4.7 Bolt pretensions for ϕ 3/4" x 2 1/2" bolts (1 1/4" in grip) in the connection on University of Toronto Teaching Design Aid Structure

Test Category (1)	Bolt # (2)	ΔL (in.) (3)	$T_c = K_u^0(\Delta L)$ (kips) (4)	$\frac{T_c}{T_m}$ (5)	Average (6)	Standard Deviation (7)
installed bolts	1	0.0030	20.2	0.72	0.75	0.04
	2	0.0034	22.9	0.82		
	3	0.0030	20.2	0.72		
	4	0.0033	22.2	0.79		
	5	0.0033	22.2	0.79		
	6	0.0029	19.5	0.70		
	7	0.0031	20.9	0.74		
	8	0.0030	20.2	0.72		
snug-tightened bolts	1	0.0034	22.9	0.82	0.68	0.10
	2	0.0026	17.5	0.62		
	3	0.0029	19.5	0.70		
	4	0.0024	16.1	0.58		

Note: ΔL = change in bolt length during loosening; T_c = calibrated tension; K_u^0 = calibrated bolt stiffness from direct tension test (6729 kips/in.); T_m = specified minimum pretension (28 kips)

Table 4.8 on the next page shows the pretension results of those 3/4 in. diameter by 3 1/4 in. long bolts. They were very close to those in Table 4.8 for the bolts that were from the same metal keg and were installed in the 3-plate steel joint. The grip length of bolts in the connection was 2 1/4 in.; this was 1/4 in. longer than that of the bolts installed in the 3-plate joints. In addition, all the bolts in this test category were installed on hot summer days (mid July~ mid August). The average temperature of the bolts when installed was about 30 °C, a little higher than that for room temperature installation. It also can be seen from Figure 4.11 that the bolts installed in the connection performed in the same manner as those in the 3-plate joints, that is, as the exposure period increased the average installed bolt pretension decreased. This demonstrated that the Bolt Gage technique was also suitable for the field testing.

Table 4.8 Bolt pretensions for ϕ 3/4" x 3 1/4" bolts (2 1/4" in grip) installed in the connection on UT Teaching Design Aid Structure

Test Category (1)	Bolt # (2)	ΔL (in.) (3)	$T_c = K_u^0(\Delta L)$ (kips) (4)	$\frac{T_c}{T_m}$ (5)	Average (6)	Standard Deviation (7)
as-received	1	0.0070	30.0	1.07	1.08	0.01
	2	0.0071	30.5	1.09		
	3	0.0071	30.5	1.09		
	4	0.0069	29.6	1.06		
2 weeks	1	0.0070	30.0	1.07	1.04	0.03
	2	0.0068	29.2	1.04		
	3	0.0065	27.9	1.00		
	4	0.0069	29.6	1.06		
4 weeks	1	0.0061	26.2	0.94	0.94	0.06
	2	0.0056	24.0	0.86		
	3	0.0063	27.0	0.97		
	4	0.0065	27.9	1.00		
8 weeks	1	0.0052	22.3	0.80	0.86	0.06
	2	0.0058	24.9	0.89		
	3	0.0054	23.2	0.83		
	4	0.0060	25.8	0.92		
wet bolts	1	0.0060	25.8	0.92	0.97	0.05
	2	0.0067	28.8	1.03		
	3	0.0061	26.2	0.94		
	4	0.0065	27.9	1.00		

Note: ΔL = change in bolt length during loosening; T_c = calibrated tension; K_u^0 = calibrated bolt stiffness from direct tension test (4292 kips/in.); T_m = specified minimum pretension (28 kips)

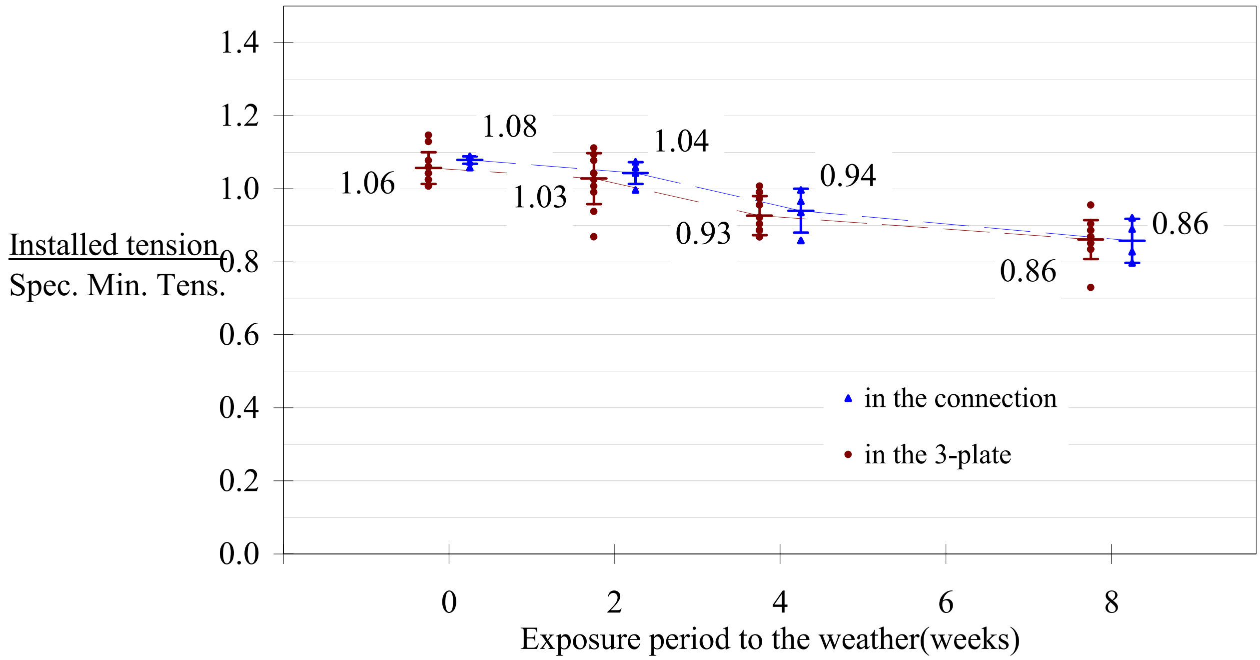


Figure 4.11 Comparison of ϕ 3/4” x 3 1/4” bolts (A) installed in the connection and in the 3-plate joints

4.4 DELAYED INSTALLATION AND RELATED WEATHERING EFFECTS

The pretension developed by the twist-off bolts in practical field applications when installation is delayed is the major focus of this study. To simulate the twist-off bolt installation in the field, a group of tests were conducted on a simple steel 3-plate joint. The bolts were installed in the 3-plate joints as they would be installed in the field; they were first brought to a snug-tight condition and the joint was placed on the roof of the Galbraith Building at 35 St. George Street in Toronto with full exposure to weather. The bolts were finally tightened with the automatic TC wrench after different exposure durations. Additionally, some fastener assemblies were placed on the roof separately and were installed in the Skidmore-Wilhelm after the same exposure duration for field verification. These included bolt assemblies that were disassembled and assemblies that were placed on roof in the same condition in which they were taken out from the keg; i.e. the nut and washer were on the bolt.

The bolt temperature at the installation may have some effects on the bolt pretension because the lubricant may act differently under different temperatures. To examine the temperature effect, some bolts were exposed and installed in the heat of summer and some in the cold of winter. Moreover, it was expected that the lubricant might behave differently if the bolt is in a wet condition, such as being exposed to rain or snow before or during installation; thus the wet bolt installation tests were conducted to examine the effect of wetness on the as-received bolts.

4.4.1 Test Apparatus: 3-plate steel joint

The 3-plate joint was designed according to RCSC Specification's (2004) slip specimen, and fabricated by the WALTERS Steel company. The details of the joint are presented in Figure 4.12 and a picture of the assembly is shown in Figure 4.13. The steel used for the plates was CSA G40.21-M300W or equivalent. The edges of the plate were sawn or flame cut and all the plates were identical except for thickness. With consideration of the variation in length of bolt that would be tested in the joint, the thickness of the plates was adjusted to satisfy the minimum and maximum grip length requirements in RCSC Specification (2004) for the bolts with different length. All the bolt holes were drilled holes. The holes were off-center of the plate width so that when assembled, the joint could also be used for a standard RCSC Specification slip test specimen. All the dimensions relative to a single bolt were proportional to those in the Appendix A of RCSC Specification (2004). Based on the experience gained with the three bolt prototype joint, the number of bolt holes was increased to four per specimen to improve the statistical sample size without making the specimen size impractical for handling and assembly.

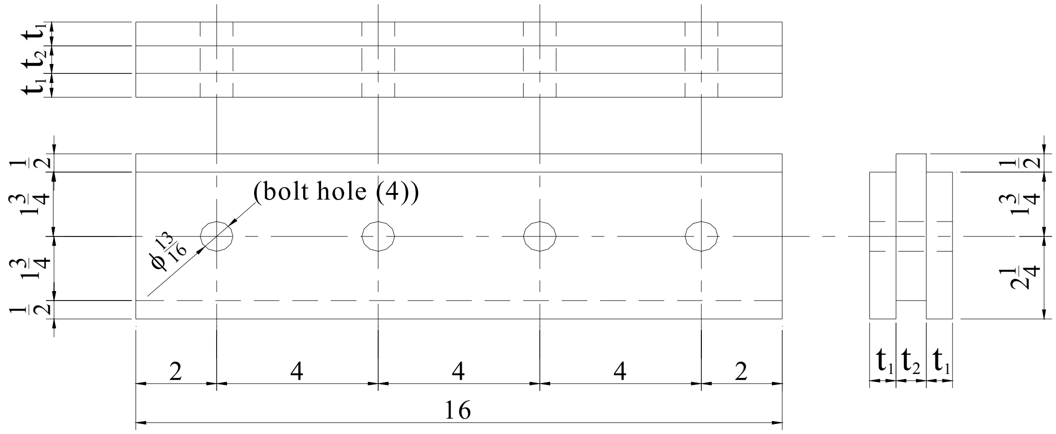


Figure 4.12 Dimensions of 3-plate joint (unit: in.)

Figure 4.13 Typical 3-plate joint

4.4.2 Test Parameters (delayed installation samples)

Bolts were tested in ten conditions as described below. For each category, 12 bolts from each manufacturer were installed in three 3-plate joints and tested. In addition, 3 bolts from each manufacturer were exposed to the weather separately under the same conditions as the bolted joints, and were installed in Skidmore-Wilhelm calibrator for verification. Figure 4.14 shows the picture of a typical weathered sample. It should be noted that parameters 3, 5 and 7 were only investigated on bolts from company A. This variation in procedure was introduced on the basis of the results from the initial delayed installation tests.

1. As-received bolts in the Skidmore tension calibrator.
2. As-received bolts in steel joints.
3. Assemblies (bolt, nut and washer) weathered separately (see Figure 4.15) for 2, 4, and 8 weeks and tested in the Skidmore
4. Assemblies (bolt, nut and washer) weathered as taken out of the keg, i.e. assembled, (see Figure 4.14) for 2, 4, and 8 weeks and tested in the Skidmore
5. Bolts loosely placed in simulated steel joints with full exposure to weather for 2, 4 and 8 weeks.
6. Bolts snug tightened in simulated steel joints with full exposure to weather for 2, 4 and 8 weeks.
7. Bolts snug tightened in simulated steel joints with full exposure to weather for 2, 4 and 8 weeks and removed, reinserted and snug tightened again before installation.
8. Bolts installed at high temperature (summer conditions).
9. Bolts installed at low temperature (winter conditions).
10. Bolts installed in a visibly wet condition.

Figure 4.14 Typical weathered sample on the roof

The purpose of the separate assemblies exposed to the atmosphere was to compare the behavior of weathered fasteners installed in the Skidmore tension calibrator versus that of snug tightened bolts installed in the simulated steel joints. The test essentially observes the RCSC Specification (2004) requirement that allows the pre-installation verification in the tension calibrators to be done with bolt assemblies removed from the steelwork or with extra assemblies that were set aside to experience the same degree of exposure at the time of placement. This test represents the latter condition.

Furthermore, the separately weathered assemblies were divided into two categories to gain a better understanding of the effect of rusting on the achieved pretension. The first category (test parameter number three) was aimed at achieving the greatest rusting effect on the assembly since the bolt, nut and washer were all weathered separate from one another as illustrated in Figure 4.15. The second category (test parameter number four) was intended to reproduce a typical arrangement in which the fasteners would most likely be weathered in real construction practice. Both of these categories were tested only in the Skidmore tension calibrator.

Figure 4.15 Arrangement of assemblies from test parameter three

The main goal of the loosely placed bolts in simulated steel joints (test parameter number five) series of tests was to have an intermediate point for comparison between the pretensions developed by loosely weathered assemblies and bolts weathered in snug tightened condition in simulated steel joints. Moreover, during construction, it is not uncommon to see fasteners loosely placed in the steelwork while all the elements are being erected. As a result, it was considered important to also examine the behavior of twist-off bolts under this condition. This parameter was investigated only on bolts from Company A.

The weathering of bolt assemblies snug tightened in steel joints was considered the most typical scenario of delayed installation that would occur in practice. In this way, a baseline for their performance could be established and compared to the fasteners installed with different procedure or variations of this scenario. Thus, the isolated parametric effect of the delayed installation on the achieved pretension could be determined.

Test parameter seven was considered based on observations made during the laboratory work. Results suggested that a possible reason for the different behavior, after exposure to the environment, of twist-off fasteners installed in the Skidmore compared to those in the steel joints might be the fact that bolts tested in the tension calibrator typically have their nut run along the threads just before being installed. As a result, the premise was that the removal of the nut before installation could alter the thread conditions and lead to different performance compared to the assembly that had remained in snug tight condition for the duration of the exposure period. Consequently, this parameter was examined as a potential method for minimizing the loss of pretension due to delayed installation. This parametric variation was also only performed on bolts from company A.

Finally, the last three parametric variations were considered to reflect temperature and moisture extremes that are realistic to construction practice. Temperature extremes were those found in Toronto, Ontario during the summer and winter seasons of 2003 and 2004. Moisture effects were observed while conducting the delayed tightening tests on the roof of the Galbraith building at the University of Toronto as well as during the separate tests that were conducted to examine only the moisture parameter.

4.4.3 Test Specimen Description

Bolt assemblies supplied by four companies were tested to compare the performance of the twist-off bolts with different lubrication conditions associated with their source as well as with the exposure, the lubricant used and the conditions at the time of installation. According to grip length requirement of bolts in the RCSC Specification, the grip length for the 3 in. long bolts is about 1 7/8 in.; this grip length was achieved by placing one 3/4 in. thick plate in the middle and two 1/2 in. thick plates aside in the 3-plate joint. The nominal thickness of the washer in the fastener assembly is 3/16 in., but in reality, the measured thicknesses of the washers in the fastener assemblies from these manufacturers were all about 1/8 in. Thus, the grip length of 3 in. long bolt is 3/4 + 2(1/2) + 1/ 8 = 1 7/8 in. For the 3 1/4 in. long bolt, the grip length was 2 in.; this was provided by the same 3-plate joint assembly as described above for 3 in. long bolt with an additional washer placed under the bolt head. For 2 3/4 in. long bolt, the grip length was 1 5/8 in.; this was provided by three 1/2 in. thick plates and a washer. Table 4.9 contains a detailed numbering scheme of the 3 plate joints and the bolts that were used.

Table 4.9 Plates and bolts numbering scheme

Plate number definition

Plate Number (1)	Manufacturer (2)	Bolt Length (in.) (3)	Test Category (4)	Joint # (5)	Plate # (6)
Aa(X)-Yy	A	3 1/4	X	Y	y
Bb(X)-Yy	B	3	X	Y	y
Cc(X)-Yy	C	2 3/4	X	Y	y
Dc(X)-Yy	D	2 3/4	X	Y	y

Bolt number definition

	Bolt Number (1)	Manufacturer (2)	Bolt Length (in.) (3)	Test Category (4)	Joint # (5)	Bolt # (6)
Bolts in the steel joints	Aa(X)-YZ	A	3 1/4	X	Y	Z
	Bb(X)-YZ	B	3	X	Y	Z
	Cc(X)-YZ	C	2 3/4	X	Y	Z
	Dc(X)-YZ	D	2 3/4	X	Y	Z
Bolts in the Skidmore (verification)	Aa(X)-z	A	3 1/4	X	N/A	z
	Bb(X)-z	B	3	X	N/A	z
	Cc(X)-z	C	2 3/4	X	N/A	z
	Dc(X)-z	D	2 3/4	X	N/A	z

Note: X = 0, 2, 4, 8, h, c, and w, refer to the test category 1, 2, 3, 4, 5, 6, 7, separately as stated in Section ;

Y = 1, 2, and 3, refer to the three joints in each test category;

Z = 1, 2, 3, and 4, refer to the four bolts in each joint;

z = 1, 2, and 3, refer to the three bolts weathered or treated separately in each category;

y = t, m, and b, refer to the three plates in each joint; t = top, refers to the plate close to the bolt head; m = middle, refers to the plate in the middle of the joint; b = bottom, refers to the plate close to the end of the bolt.

Example: Aa(2)-11 refers to the No. 1 type A bolt positioned in the No. 1 joint in the test category of two weeks weathering. Type A bolt is the 3 1/4 long bolt from manufacturer A.

Bb(h)-1t refers to the top plate in the No. 1 joint of type B bolts in the test category of hot weather installation. Type B bolt is the 3 in. long bolt from manufacturer B.

4.4.4 General Test Procedure

For those bolts installed in the 3-plate joint, bolts were first inserted in the 3-plate joints and turned to snug-tight condition with an ordinary spud wrench and full manual effort, and then the three 3-plate joint specimens in each category were placed on the roof of the Galbraith building. The roof of the Galbraith building provided the joints and bolts with full exposure to the elements. Some bolt assemblies, that were to be used later for field verification in the Skidmore, were put in a net bag and placed near those joint specimens to be tested at the same time. Shown as in Figure 4.14, the bolts and plates were all labeled with a white paint marker with their numbers following the numbering identification scheme described in Table 4.9.

Before the bolts were installed in the steel joints, the pre-installation verifications were performed in Skidmore-Wilhelm calibrator (see Figure 4.16). For each test category, 3 bolts that were weathered separately under the same condition as those in the bolted joints were installed in Skidmore with the same grip length as in the 3-plate joint, and the bolt pretensions were recorded. The bolts were loosened using the dial-indicating manual torque wrench, and the loosening torque was recorded for comparison. Since Model MS Skidmore-Wilhelm bolt tension calibrator was designed for short structural fasteners, modifications were made to achieve approximately the same grip length of the bolts of various lengths as used in the steel specimens. The original front plate of the model MS was replaced by new thicker plates with various thicknesses as required. The Skidmore had its calibration checked with the MTS machine after modification. In addition, after all the tests were completed, the Skidmore was tested again with a hydraulic jack and a load cell to revalidate its accuracy.

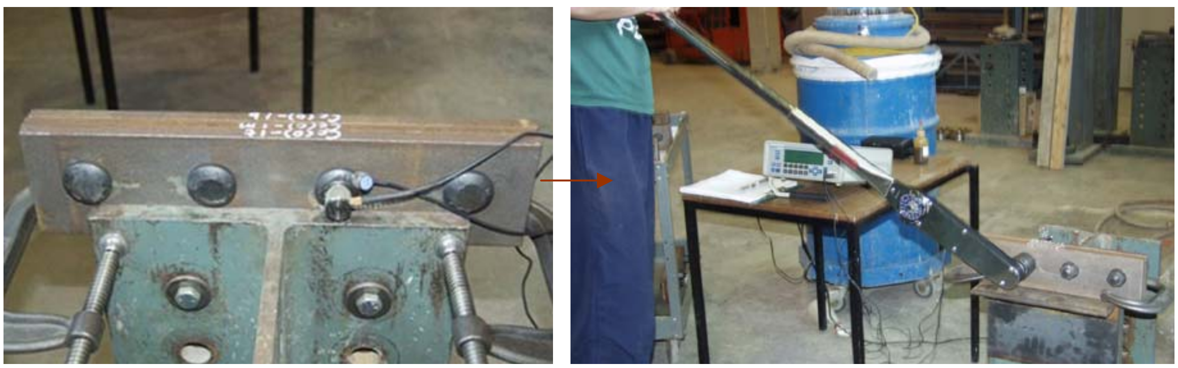
The cold weather or hot weather installation test was performed by simply placing the snug tightened 3-plate joints on the roof for a few hours in the hot summer day or cold winter day. The bolts were installed on the roof after these few hours of exposure, and the temperature of the axposed bolts was measured using the temperature transducer of the Bolt Gage.

The wet bolt assembly installation tests were performed on visibly wet parts. The disassembled bolt assemblies were submerged in tap water to make sure that the threads on the bolts and nuts and the washers were all wet. Then the bolts were inserted in the joint, turned to a snug-tight condition, and then installed immediately afterward.

Figure 4.16 Skidmore pre-installation verification

The installations of the bolts in the joint from snug-tight condition proceeded from the bolts in the center part of the joint to those on the edges using the automatic TC wrench in a single continuous operation. After installation, the Bolt Gage was employed to measure the elongation of the bolt. With the transducer remaining on the bolt head, the nut was loosened with a dial-indicating torque wrench, and at the same time the change in bolt length was determined with the Bolt Gage. The loosening torque was monitored to check if the torque was typical of an elastic unloading. The photographs in Figure 4.17 illustrate the test procedure for bolt installation in the steel joint in the laboratory.

Snug tightening Installation Head Preparation



Length measurement Nut loosening

Figure 4.17 General test procedure for bolt installation in the steel joint

4.4.5 Results and Discussion of the Tests from the Delayed Installation and Related Weathering effects

This section shows the results from the delayed installation, temperature and moisture experiments described above. It also presents comparisons between the data from the Skidmore and the simulated steel joints and discussion of the results.

The first visual observation was that assemblies with the bolt, nut and washer exposed to weather separately became progressively rustier. As seen in Figures 4.18 to 4.20, the bolts gradually developed the characteristic brown color as the exposure period increased. However, no thread damage or deterioration of the threads could be established. Although the fasteners seemed more rusted as they were exposed to the environmental effects for a longer period, there was no obvious deterioration in the way the nut behaved when turned by hand on the bolt when compared to an assembly in the as-received condition.

Figure 4.18 Assemblies with the bolt, nut and washer weathered separately for 2 weeks (Company A)

Figure 4.19 Assemblies with the bolt, nut and washer weathered separately for 4 weeks (Company A)

Figure 4.20 Assemblies with the bolt, nut and washer weathered separately for 8 weeks (Company A)

Next, the bolt calibrated tensions were derived from Equation (3.7), $T_c = K_u^o \, \Delta L$, where ΔL is the change in bolt length during the bolt load releasing process and was recorded by the Bolt Gage; and K_u^o was calibrated from the direct tension test. As described previously, for ϕ 3/4” x 3 1/4” bolts from company A with grip length of 2”, K_u^o = 4862 kips/in.; for the bolts from the second lot from company A, K_u^o = 5021 kips/in.; for ϕ 3/4” x 3” bolts from manufacturer B with grip length of 1 7/8”, K_u^o = 5061 kips/in.; for ϕ 3/4” x 2 3/4” bolts from company C with grip length of 1 5/8”, K_u^o = 5651 kips/in.; and for ϕ 3/4” x 2 3/ 4” bolts from company D with grip length of 1 5/8”, K_u^o = 5628 kips/in. The average bolt tension results are presented in the following tables and figures.

Table 4.10 Pretensions for ϕ 3/4” x 3 1/4” bolts (A) from lot 1 snug- tightened in steel joints

Test Category (1)	Number Tested (2)	Average T_c (kips) (3)	$\frac{T_c}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_c}{T_u}$ (6)
As-received	12	29.6	1.06	0.04	0.61
2 weeks	12	28.8	1.03	0.07	0.60
4 weeks	12	25.9	0.93	0.05	0.54
8 weeks	12	24.1	0.86	0.05	0.50
low temp. (-4 ^oC)	12	26.7	0.96	0.05	0.55
high temp.(41 ^oC)	12	31.0	1.11	0.06	0.64
wet bolt	12	27.4	0.98	0.06	0.57

Note: T_c = calibrated tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (48.2 kips)

Table 4.11 Pretensions for ϕ 3/4” x 3 1/4” bolts (A) from lot 1 in Skidmore

Test Category (1)	Number Tested (2)	Average T_s (kips) (3)	$\frac{T_s}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_s}{T_u}$ (6)
As-received	3	31.0	1.11	0.03	0.64
2 weeks	3	30.7	1.10	0.08	0.64
4 weeks	3	31.0	1.11	0.02	0.64
8 weeks	3	31.0	1.11	0.06	0.64
wet bolt	3	30.8	1.10	0.02	0.64

Note: T_s = Skidmore tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (48.2 kips)

Table 4.12 Pretensions for ϕ 3/4” x 3 1/4” bolts (A) from lot 2 snug- tightened in steel joints

Test Category (1)	Number Tested (2)	Average T_c (kips) (3)	$\frac{T_c}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_c}{T_u}$ (6)
As-received	12	33.6	1.20	0.04	0.66
2 weeks	12	32.1	1.15	0.08	0.63
4 weeks	12	30.5	1.09	0.06	0.60
8 weeks	12	30.7	1.10	0.08	0.60

Note: T_c = calibrated tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (51.0 kips)

Table 4.13 Pretensions for ϕ 3/4” x 3 1/4” bolts (A) from lot 2 in Skidmore

Test Category (1)	Number Tested (2)	Average T_s (kips) (3)	$\frac{T_s}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_s}{T_u}$ (6)
As-received	3	35.5	1.27	0.02	0.70
2 weeks	5	34.8	1.24	0.03	0.68
4 weeks	5	33.9	1.21	0.04	0.66
8 weeks	5	32.3	1.15	0.04	0.63

Note: T_s = Skidmore tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (51.0 kips)

Table 4.14 Pretensions for ϕ 3/4” x 3 1/4” bolts (A) from lot 2 loosely placed in steel joints during exposure to environment

Test Category (1)	Number Tested (2)	Average T_c (kips) (3)	$\frac{T_c}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_c}{T_u}$ (6)
2 weeks	12	31.0	1.11	0.07	0.61
4 weeks	12	29.5	1.05	0.08	0.58
8 weeks	12	23.8	0.85	0.04	0.47

Note: T_c = calibrated tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (51.0 kips)

Table 4.15 Pretensions for ϕ 3/4” x 3 1/4” bolts (A) from lot 2, initially snug tightened in steel joints and re-snugged before installation

Test Category (1)	Number Tested (2)	Average T_c (kips) (3)	$\frac{T_c}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_c}{T_u}$ (6)
2 weeks	12	32.3	1.15	0.05	0.63
4 weeks	12	31.7	1.13	0.07	0.62
8 weeks	12	29.1	1.04	0.04	0.57

Note: T_c = calibrated tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (51.0 kips)

Figures 4.21 (company A lot 1) and 4.22 (company A lot 2) graphically summarize the pretensions achieved by these assemblies in the Skidmore, compared to the preloads obtained from the fasteners that were snug tightened in the steel joints. The y-axis of the plot is the ratio of achieved pretension divided by the minimum specified pretension, while the x-axis indicates the exposure period. For example, in Figure 4.21 the left most value of 1.11 for 0 weeks of exposure indicates that fasteners installed in the Skidmore in the as-received condition achieved a mean pretension 11% higher than the minimum specified and the bolts for the same conditions tightened in the steel joints reached a mean pretension of 6% higher than minimum. Similar numbers for lot 2 from company A are found in Figure 4.22 to be 27% and 20 %.

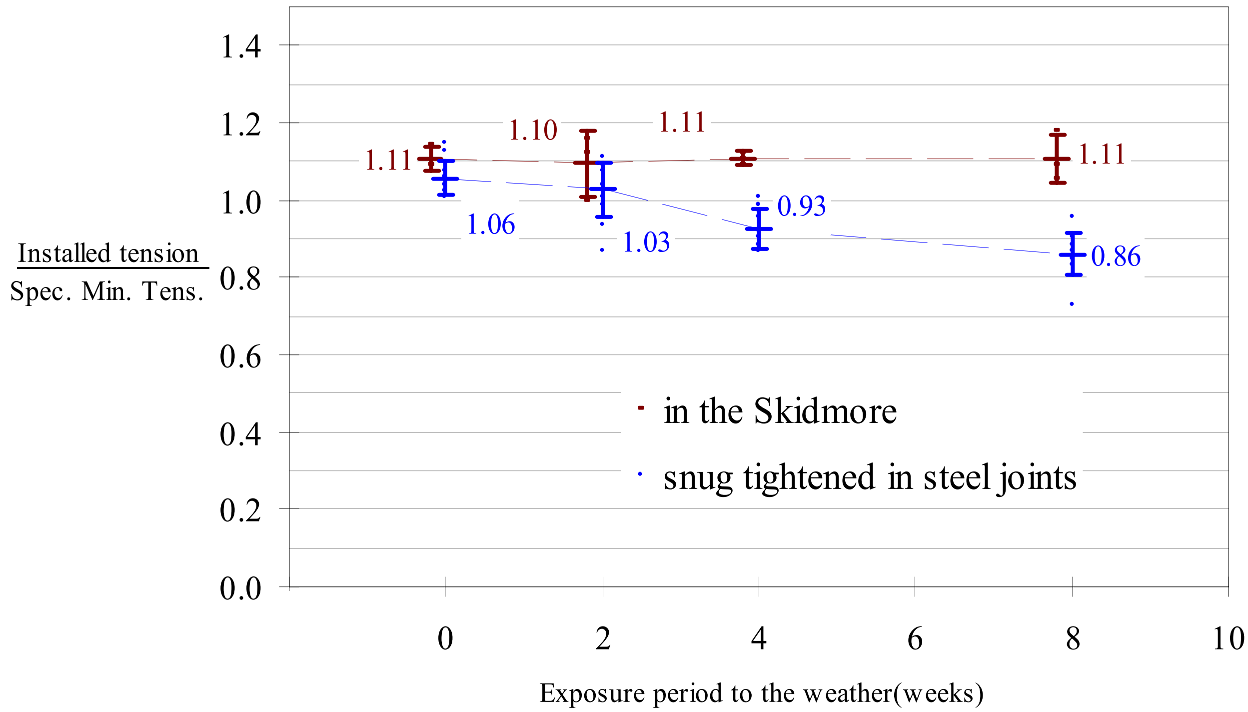


Figure 4.21 Calibrated tension /specified minimum tension for ϕ 3/4” x 3 1/4” bolts (A) from lot 1 shown as a function of time

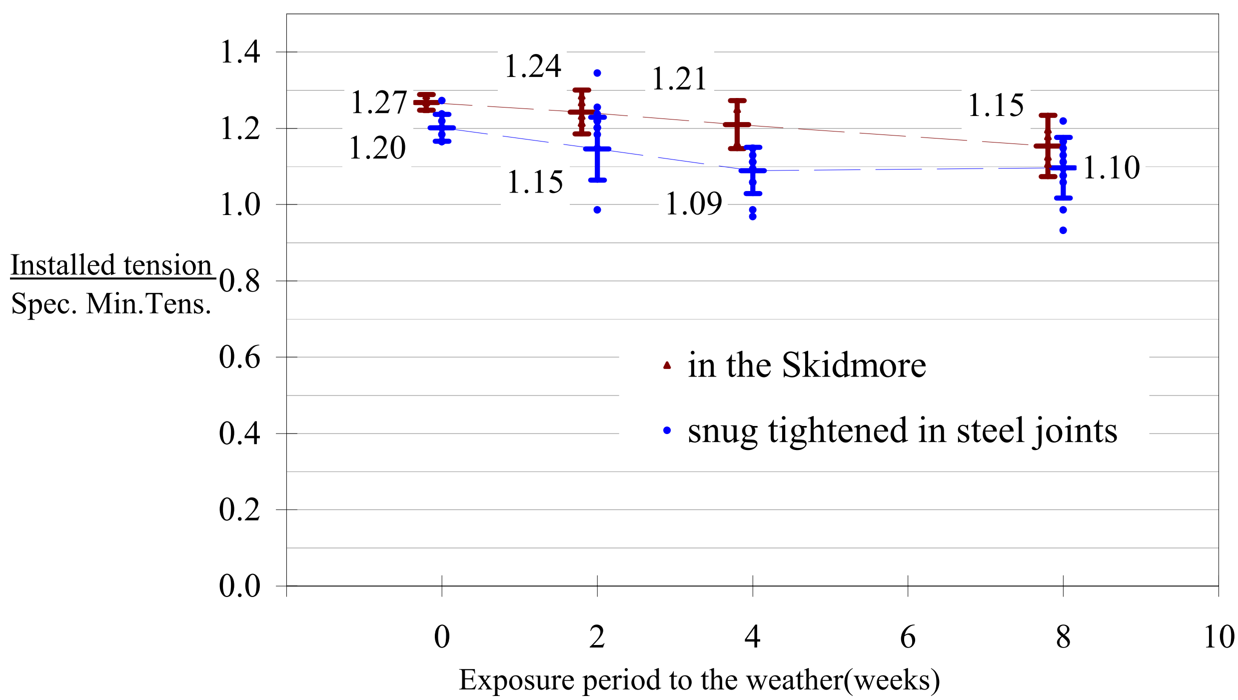


Figure 4.22 Calibrated tension /specified minimum tension for ϕ 3/4” x 3 1/4” bolts (A) from lot 2 shown as a function of time

From these figures, it can also be observed that all bolts installed in the Skidmore exceeded the minimum specified pretension. Furthermore, in Figure 4.22 the pretensions achieved in the tension calibrator decreased in a linear fashion with increase in exposure time and with visibly observed rusting. These were the assemblies where each part (bolt, nut and washer) was weathered separately, while in Figure 4.21 the assemblies installed in the Skidmore were exposed to the environment as they were taken out of the lot, i.e., with the nut and washer on the bolt. It can be seen that the latter showed no deterioration in achieved pretension with increase in the exposure period.

Figure 4.23 presents the same results from the fasteners tested in the Skidmore compared to the pretensions achieved by the bolts that were loosely placed in the steel joints before exposure to the environment.

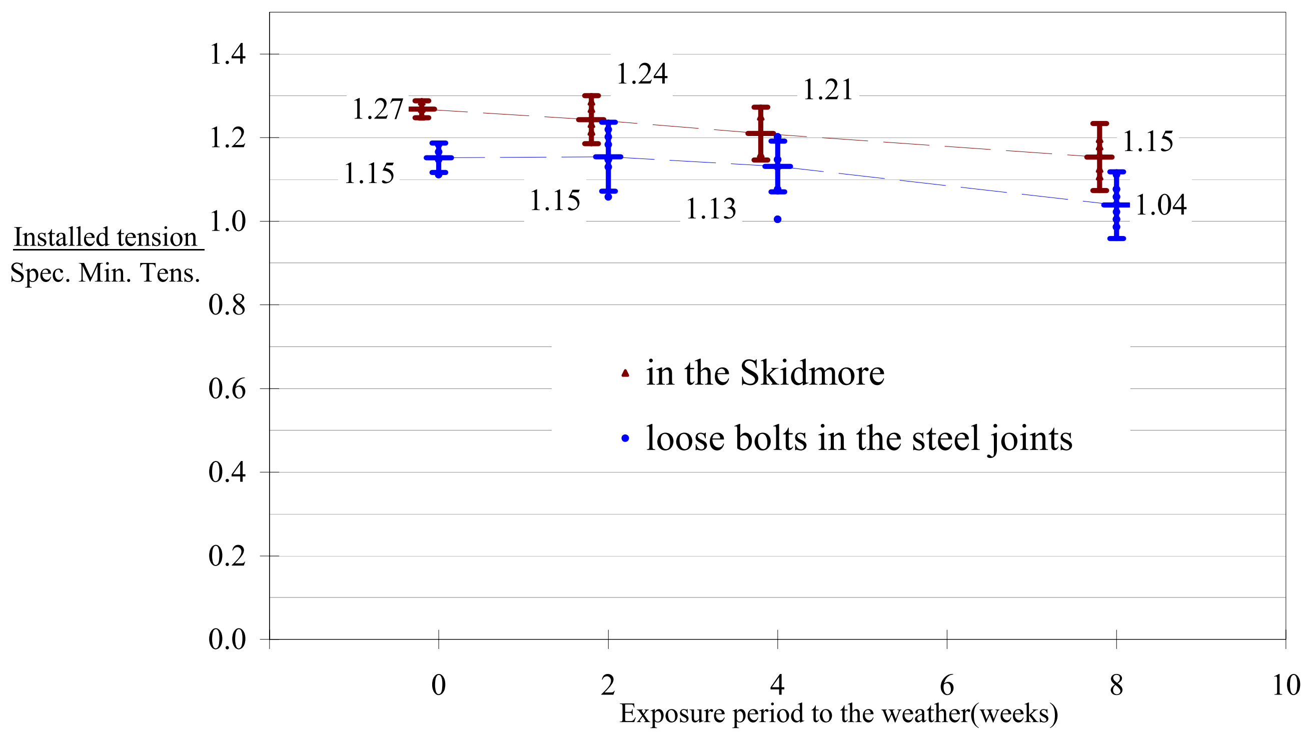


Figure 4.23 Calibrated tension /specified minimum tension
for ϕ 3/4” x 3 1/4” bolts (A) from lot 2 shown as a function of time

Figure 4.23 indicates that the bolt assemblies left loosely placed in the steel joints during exposure to the atmosphere behave differently than the otherwise similar fasteners that were snug tightened during exposure. The average preloads for the 2 and 4 weeks series follow much more closely the decrease in pretension observed in bolts installed in the Skidmore, but were still lower. In addition, it was noticed that the lubricant and thread deterioration of the assemblies that were not snug tightened during exposure resembled those of the separately weathered assemblies that were tested in the tension calibrator, rather than those that were snug tightened in the steel joints during exposure. This result supports the findings that in general, loose assemblies have a lower rate of loss of the achieved pretension as a function of exposure period than do snug tightened bolts installed in the steelwork.

For the 8-week exposure, there was a more severe decrease in pretension and the value was only marginally higher than the minimum specified pretension. The reason for this sudden drop is likely that these bolts were installed at relatively cold temperature (+5 ^{0}C) and visible moisture was present on the assemblies. For this particular lot, it was established that each of these conditions has a negative effect on the achieved pretension. This will be discussed further later in the section.

Figure 4.24 shows the Skidmore results and they are compared to the pretensions achieved by the fasteners that were exposed to weather in snug-tight condition in the steel plates, but removed and reinserted back in the joint before installation. This was done to investigate a possible method for minimizing the loss of pretension resulting from delayed installation.

The graph shows that the performance of the resnugged bolts is very similar to the normally snug tightened assemblies for the as delivered, 2 and 4 weeks cases. The result implies that running the nut through the threads of the fastener, does not disturb the thread conditions as suggested earlier. As a result, there was no indication that the method could be used to minimize the loss of the achieved pretension.

The major difference between the plots is in the 8 week series was that the mean pretension was substantially lower than the minimum specified. The resnugged fasteners from this exposure period were the first ones to be installed together with the 8 week bolts that were loosely placed in the steel joints. This was done in outdoor conditions where the temperature was relatively low and moisture was present on the assemblies. The unsatisfactory performance of those bolts was the primary reason for discontinuing the outdoor installation because it was not possible to establish a clear basis for the performance of the fasteners when additional parameters were varied. Thus, to focus more closely on the parameters that were considered here, all other delayed installation tests for company A were performed in the laboratory, after being kept for 24 hours at room temperature to remove the moisture and temperature effects.

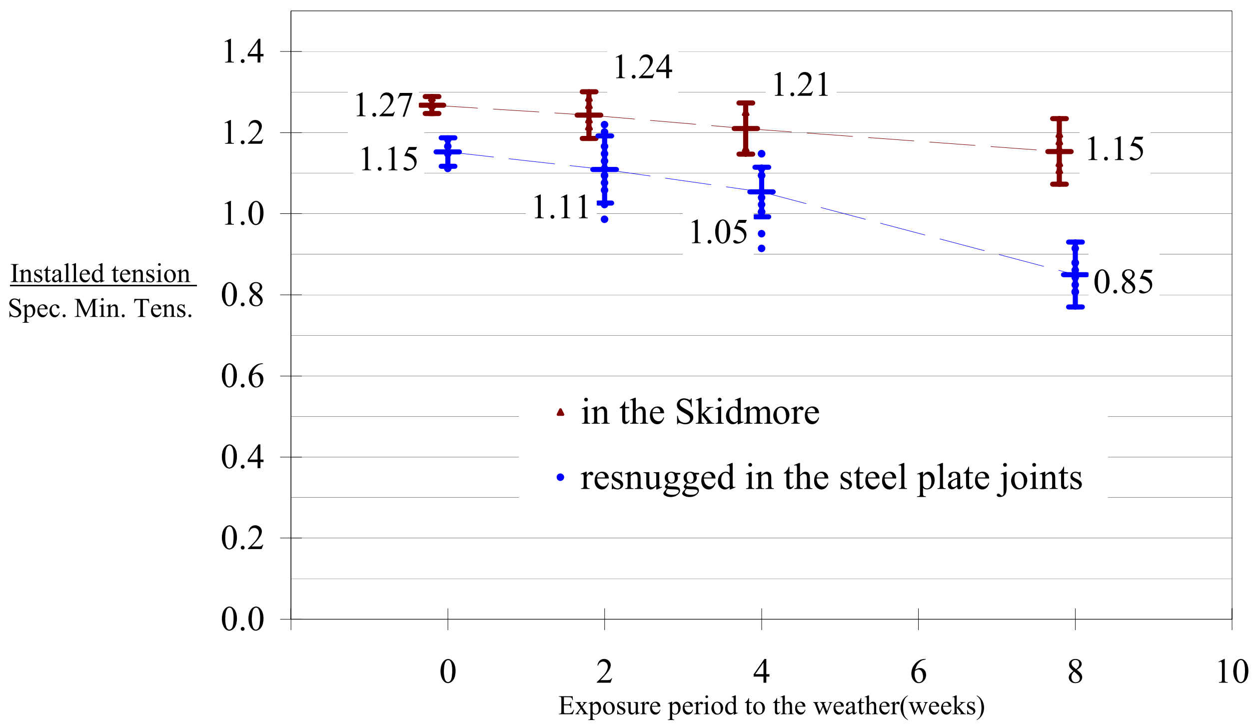


Figure 4.24 Calibrated tension /specified minimum tension

for ϕ 3/4" x 3 1/4" bolts (A) from lot 2 shown as a function of time

Although installation in outdoor conditions was discontinued to reduce the number of simultaneous parameter variations, the results from the two series prior to the change in the procedure gave a greater insight into the behavior of twist-off fasteners. Firstly, the combined negative effects of delayed installation, temperature and moisture on these fasteners produced a mean pretension 15% lower than the minimum specified. This is very important since the combination of these conditions could certainly be present in typical construction practice where the performance of such fasteners would be unacceptable. Secondly, although the 8 week bolts loosely placed in the steel joints were also installed under the same negative conditions, they achieved pretensions that exceeded the minimum specified by 4%. Together with the previous findings, the result suggests that if fasteners are likely to experience delayed installation, they will achieve higher pretensions if they are loose in the steelwork until installation.

The results from the rest of the companies are presented below. In all tests involving the simulated joints, fasteners were installed as described in the general procedure.

Table 4.16 Pretensions for ϕ 3/4" x 3" bolts (B) snug tightened in steel joints

Test Category (1)	Number Tested (2)	Average T_c (kips) (3)	$\frac{T_c}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_c}{T_u}$ (6)
As-received	12	32.9	1.18	0.05	0.62
2 weeks	12	30.8	1.10	0.05	0.58
4 weeks	12	30.4	1.09	0.05	0.58
8 weeks	12	29.9	1.07	0.07	0.57
low temp. (-4 ^oC)	12	31.8	1.14	0.06	0.60
high temp.(41 ^oC)	12	33.6	1.20	0.07	0.64
wet bolt	12	33.2	1.19	0.07	0.63

Note: T_c = calibrated tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (52.8 kips)

Table 4.17 Pretensions for ϕ 3/4" x 3" bolts (B) in Skidmore

Test Category (1)	Number Tested (2)	Average T_s (kips) (3)	$\frac{T_s}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_s}{T_u}$ (6)
As-received	3	37.5	1.34	0.03	0.71
2 weeks	3	34.7	1.24	0.01	0.66
4 weeks	3	34.7	1.24	0.04	0.66
8 weeks	3	34.7	1.24	0.03	0.66
wet bolt	3	33.2	1.19	0.02	0.63

Note: T_s = Skidmore Tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (52.8 kips)

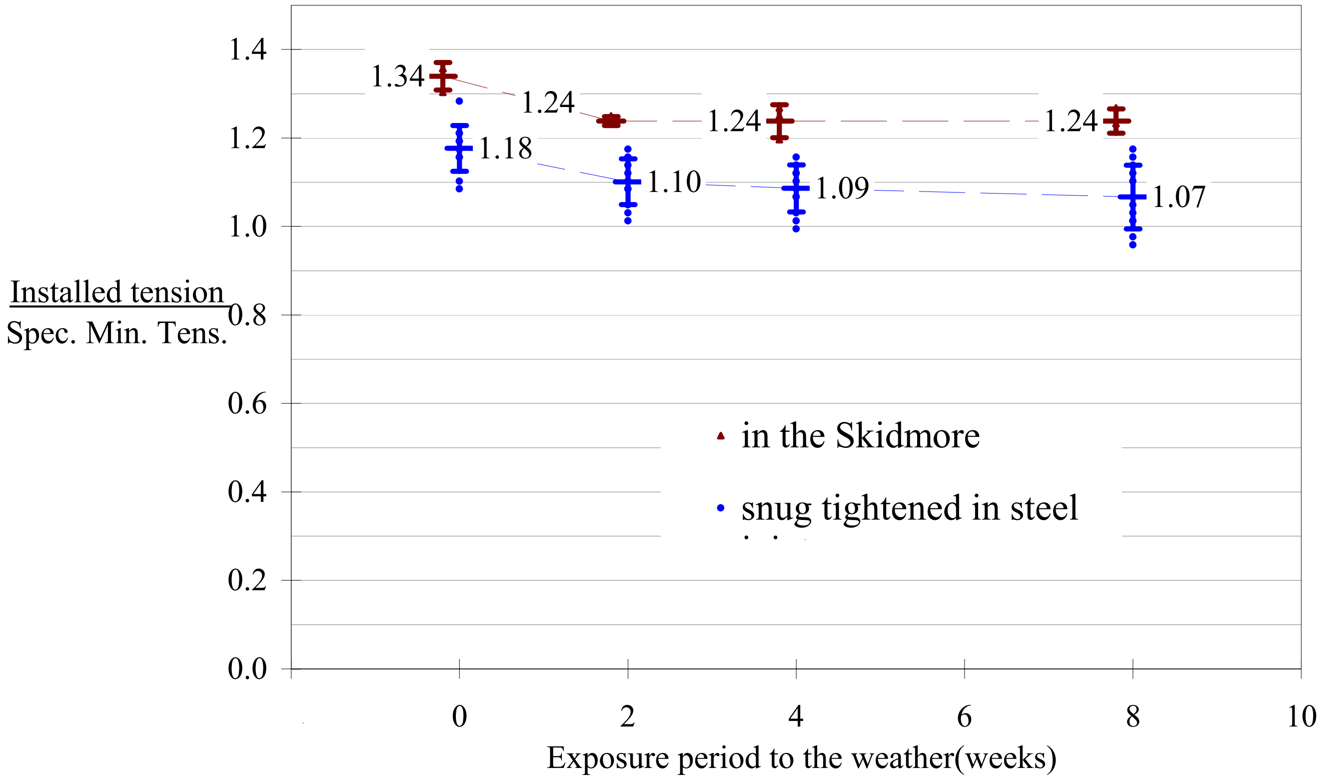


Figure 4.25 Calibrated tension /specified minimum tension for ϕ 3/4" x 3" bolts (B) shown as a function of time

Table 4.18 Pretensions for ϕ 3/4" x 2 3/4" bolts (C) snug tightened in steel joints

Test Category (1)	Number Tested (2)	Average T_c (kips) (3)	$\frac{T_c}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_c}{T_u}$ (6)
As-received	12	33.5	1.20	0.07	0.65
2 weeks	12	31.2	1.11	0.05	0.60
4 weeks	12	30.7	1.10	0.05	0.59
8 weeks	12	32.4	1.16	0.06	0.63
wet bolt	12	35.0	1.25	0.07	0.68

Note: T_c = calibrated tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (51.8 kips)

Table 4.19 Pretensions for ϕ 3/4" x 2 3/4" bolts (C) in Skidmore

Test Category (1)	Number Tested (2)	Average T_s (kips) (3)	$\frac{T_s}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_s}{T_u}$ (6)
As-received	3	36.7	1.31	0.02	0.71
2 weeks	3	37.1	1.33	0.08	0.72
4 weeks	3	34.5	1.23	0.06	0.67
8 weeks	3	36.5	1.30	0.02	0.70
wet bolt	3	39.0	1.39	0.04	0.75

Note: T_s = Skidmore tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (51.8 kips)

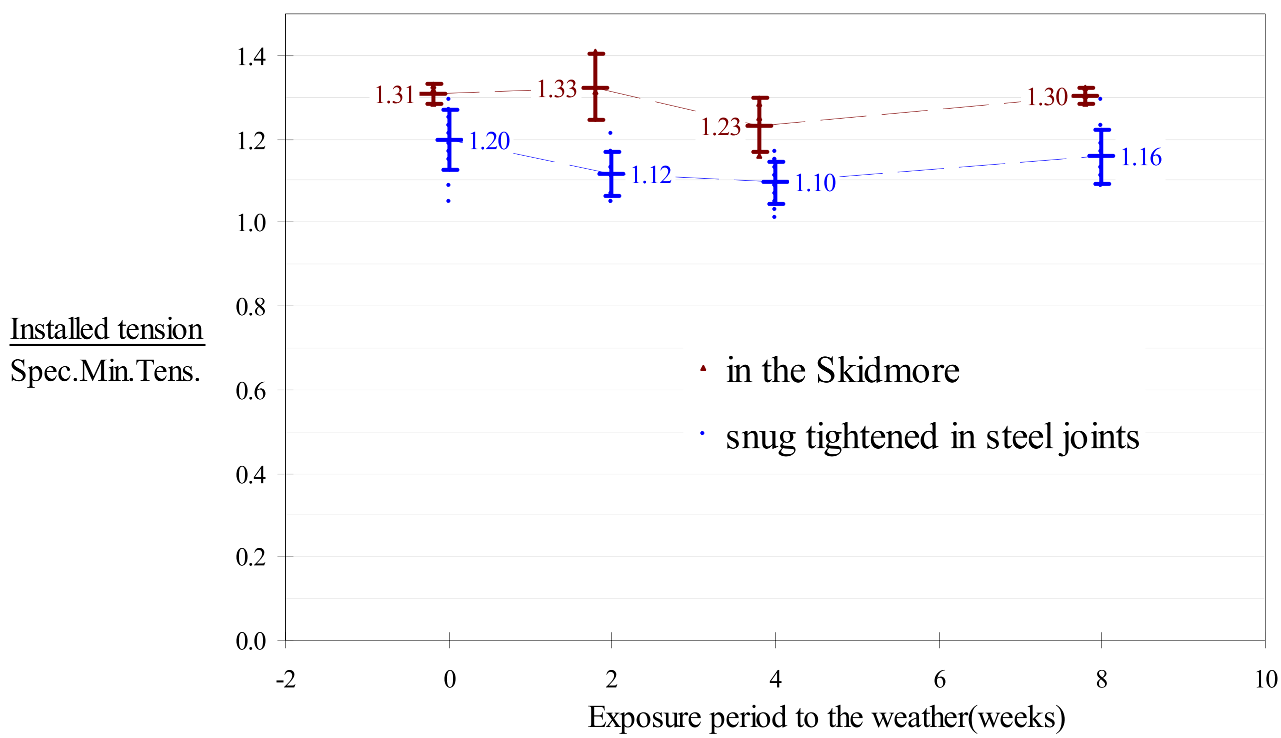


Figure 4.26 Calibrated tension /specified minimum tension for ϕ 3/4" x 2 3/4" bolts (C) shown as a function of time

Table 4.20 Pretensions for ϕ 3/4" x 2 3/4" bolts (D) snug tightened in steel joints

Test Category (1)	Number Tested (2)	Average T_c (kips) (3)	$\frac{T_c}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_c}{T_u}$ (6)
As-received	12	32.7	1.17	0.10	0.63
2 weeks	12	30.8	1.10	0.15	0.59
4 weeks	12	35.2	1.26	0.09	0.68
8 weeks	12	30.5	1.09	0.10	0.59
wet bolt	12	35.2	1.26	0.10	0.68

Note: T_c = calibrated tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (51.9 kips)

Table 4.21 Pretensions for ϕ 3/4" x 2 3/4" bolts (D) in Skidmore

Test Category (1)	Number Tested (2)	Average T_s (kips) (3)	$\frac{T_s}{T_m}$ (4)	Standard Deviation (5)	$\frac{T_s}{T_u}$ (6)
As-received	3	35.4	1.26	0.09	0.68
2 weeks	3	36.1	1.29	0.07	0.70
4 weeks	3	36.4	1.30	0.14	0.70
8 weeks	3	32.4	1.16	0.11	0.62
wet bolt	3	35.3	1.26	0.09	0.68

Note: T_s = Skidmore tension; T_m = specified minimum pretension (28 kips); T_u = ultimate strength in direct tension (51.9 kips)

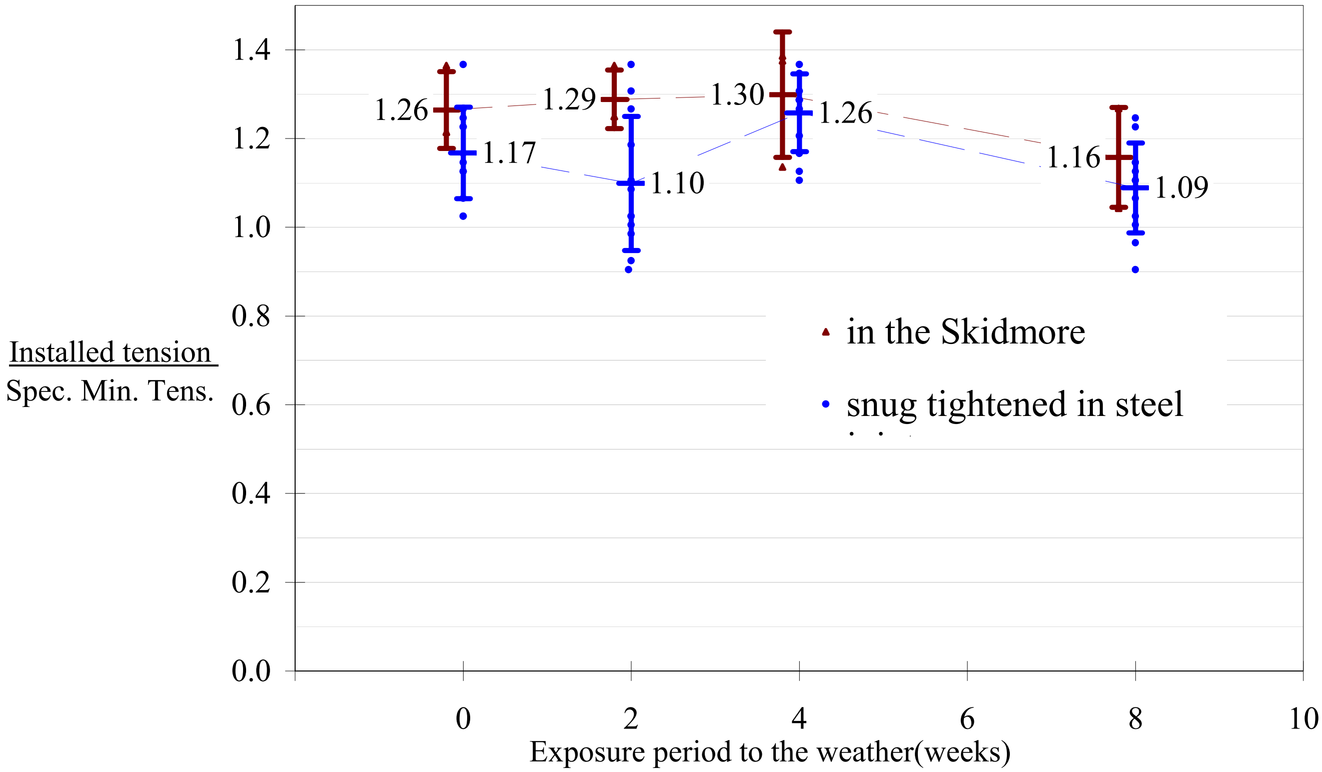


Figure 4.27 Calibrated tension /specified minimum tension for ϕ 3/4" x 2 3/4" bolts (D) shown as a function of time

As shown in Figure 4.25, the pretension results of ASTM F1852 ϕ 3/4" x 3" bolts from company B exhibited similar behavior to the lot 1 fasteners from company A. It can be seen that the bolt pretensions from the Skidmore verification were again higher than the calibrated tensions of bolts installed in the steel joints. Research by Kulak and Undershute (1994) also showed that after 2-week and 4-week exposure the bolts that were snug-tightened in a steel joint developed lower pretensions than the bolts that were exposed separately. This supports the conclusion that fasteners snug tightened in steel joints deteriorate more than the same assemblies separately exposed to the environment.

For bolts installed in the steel joints, the average pretension decreased as the bolt exposure period prior to installation increased. Further, the average pretension result from the 2-week exposure test was apparently lower than that from the as-received installation. After 4-week and 8-week exposure, the decrease slowed down. For the Skidmore verification, the decrease of average bolt pretension after 2-week exposure can be examined. After that, the average pretensions stayed at the same value. This was slightly different from the results of bolts installed in the steel joints. One explanation for this was, as described above, the thread conditions of the bolts in the steelwork are worse than those of fasteners weathered separately.

As shown earlier in Figure 4.21, for ASTM F1852 ϕ 3/4” x 3 1/4” bolts from company A, lot 1, the pretensions of bolts installed in the 3-plate joints decreased as the exposure period prior to installation increased. After 2-week exposure, the average pretension was only marginally greater than the specified minimum pretension as required by the RCSC Specification. Seen from the test data, the pretensions of some of the bolts installed after 2-week exposure were actually lower than the specified minimum pretension. After 4-week and 8-week exposure, the average pretensions were much lower than the specified minimum pretension. However, little change in average pretension is observed from the Skidmore verification over the 8 week period. These results suggest that the Skidmore-Wilhelm tension calibrator may not be a good indicator of pretension for fasteners that have experienced delayed installation.

Figure 4.26 displays the pretension results of ASTM F1852 ϕ 3/4” x 2 3/4” bolts from company C. For bolts in the steel joints, the pretension results were similar to those from bolts from company B when the bolts were tested in the as-received, 2-week, and 4-week exposure condition. The average pretension decreased apparently after 2-week exposure, while after 8-week exposure the average pretension increased a little possibly because of the heavy rainfall during the bolt exposure period between 4 weeks and 8 weeks. For bolts installed in the Skidmore, the decrease of average pretension can be observed at 4-week exposure test.

The pretension results of F1852 ϕ 3/4” x 2 3/4” bolts from manufacturer D were shown in Figure 4.27. For bolts in the joints, the average pretension decreased apparently during the first two weeks’ exposure period. However, after 4-week exposure the average pretension increased. This was probably caused by the heavy rain during the night before the test date. The bolts in the joints were in wet condition when the installation was performed. This supports the results from the wet installation tests, reported in Figure 4.29, since an increase in the achieved pretension was observed when the fasteners were installed with visible moisture present on the assembly. For bolts installed in the Skidmore, the decrease of average pretension can be seen after 8-week exposure.

To summarize the main points among companies, it was observed that the average pretensions of bolts from company B, C and D were similar, and were higher than the data for bolts from manufacturer A. From Table 4.3 it is evident that the tensile strength and the hardness of bolts from company A were lower than those from other companies although within the RCSC Specification requirements. Thus, bolts with higher tensile strength seem to achieve higher pretensions. This relationship is illustrated in Figure 4.28. The test data from reinstallation of removed bolts with turn-of-nut method is also included in the figure.

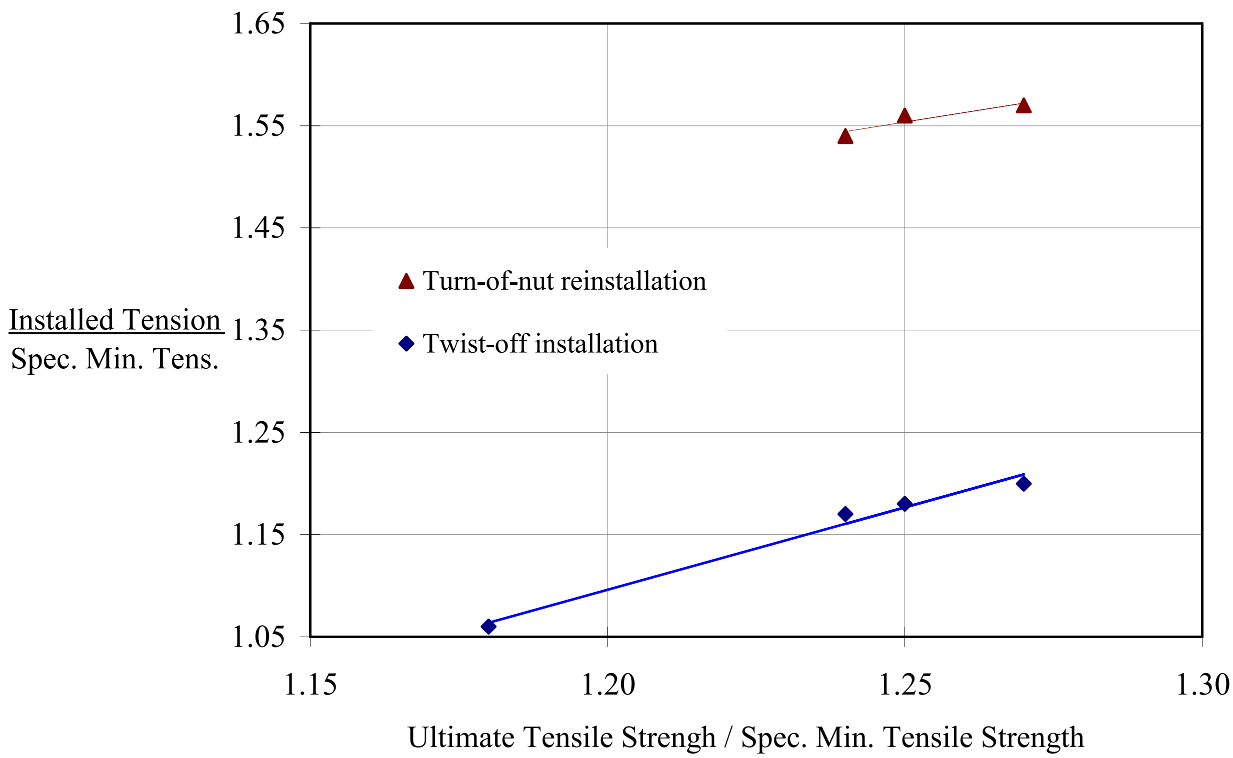


Figure 4.28 Installed tension as a function of bolt tensile strength

Observations on the appearance of lubrication on the various TC assemblies are noteworthy. The lubricants on nuts from companies B and D were quite obvious and could be smeared easily, while the lubricants on nuts from companies A and C were not visibly apparent. Comparing pretension achieved in the bolts of the same size from companies C and D, the average pretension of bolts from company D with a visibly heavier lubricant were a little lower than that of bolts from company C. In addition, the geometrical and mechanical properties of bolts from companies C and D were very similar. Thus the visibly heavier lubrication on the nuts could not be associated with performance. One could conclude that bolts with higher "as-received" installed tensions could suffer some deterioration and still meet the minimum requirements after a delay in installation.

A wet installation test was also performed on bolts from the four manufacturers. Figure 4.29 shows the installed pretension results of wet bolts versus the as-received bolts. It was observed that tap water tended to improve the bolt assembly performance for companies C and D, had little effect on the assemblies from company B, and negative effects on the performance of assemblies from manufacturer A. The result for company A is consistent with the conclusion derived earlier from the assemblies that were installed with moisture present.

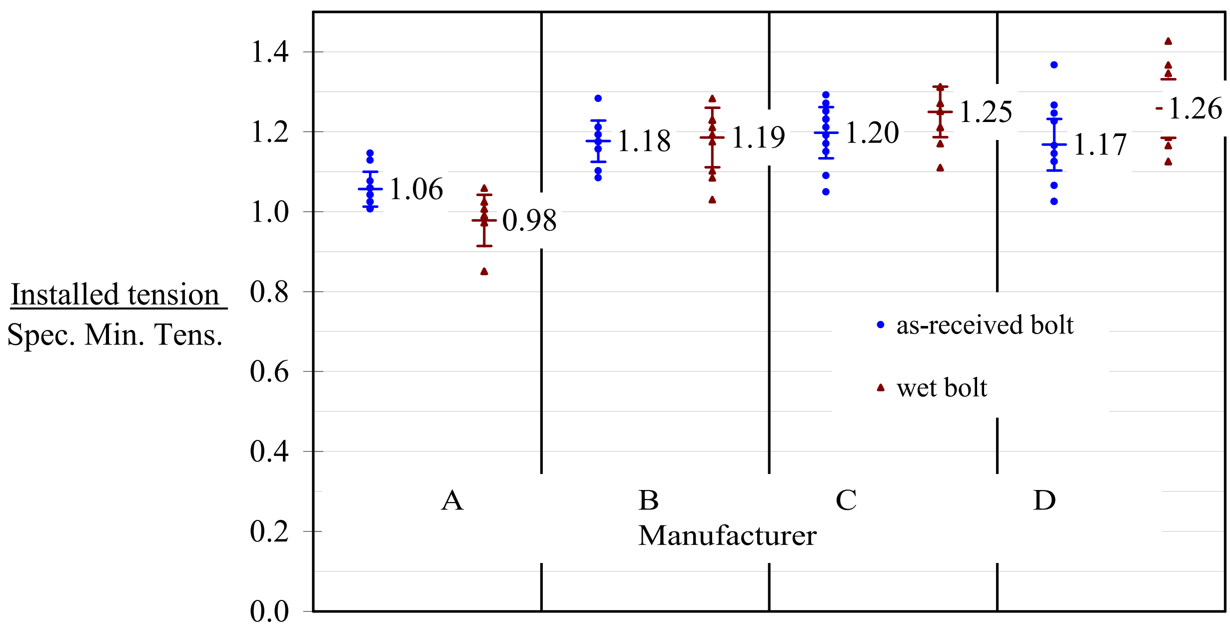


Figure 4.29 Wet bolts vs. As-received bolts

Temperature effects were investigated for bolts from manufacturer A and B. Some bolts were installed in the hot summer day, some were installed in the cold winter day, and bolts in all other conditions were installed in the lab where the room temperature was about 24 ^{o}C. The temperatures of bolts were 41^{o} C and - 4^{o} C for the high and low temperature installation tests, respectively. It can be observed from Figure 4.30 that as the bolt temperature is increased, the average pretension increased for fasteners from both manufacturers.

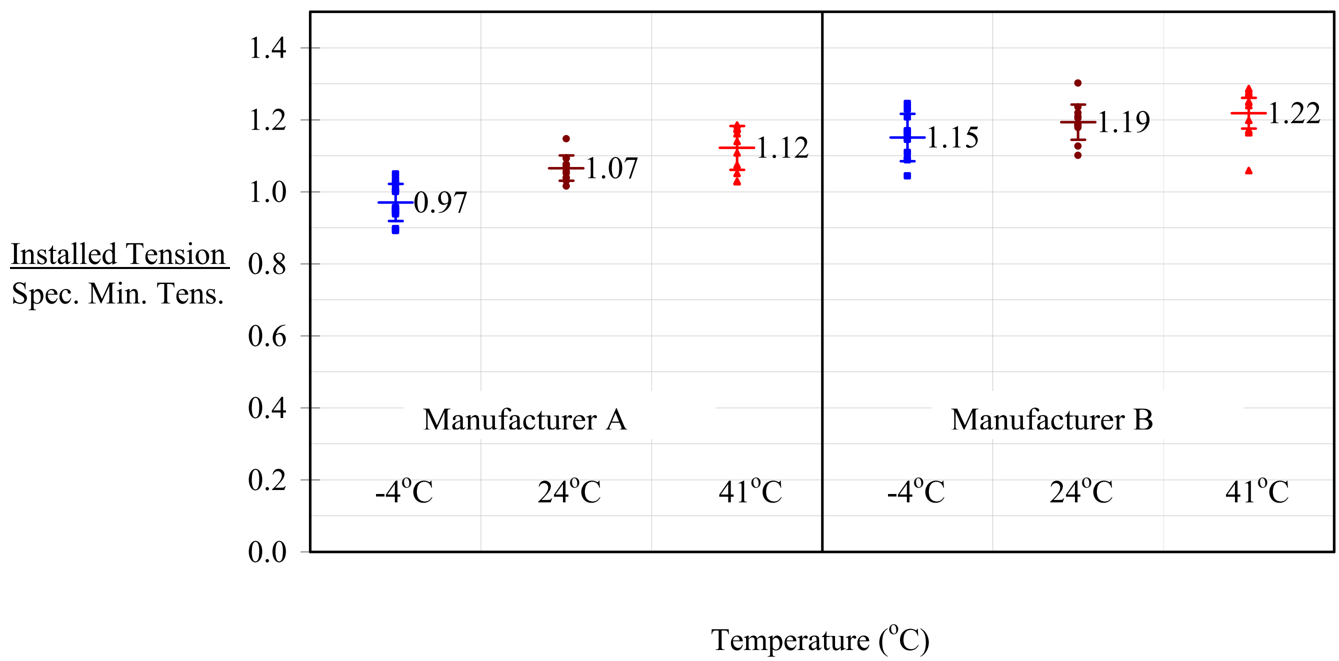


Figure 4.30 Temperature effects on achieved pretension

4.5 SLIP TESTS

The objective of the slip tests was to compare the slip resistance of newly blast cleaned steel plates versus rusted/weathered steel plates. This objective complements the main investigation on the installed pretension because both will influence the slip limit state.

The slip testing procedure generally followed the one described in Appendix A of the RCSC Bolt Specification. Bolts from lot 2 from company A and steel plates as illustrated in section 4.4.1 were used for the tests. A schematic of the test is presented in Figure 4.31.

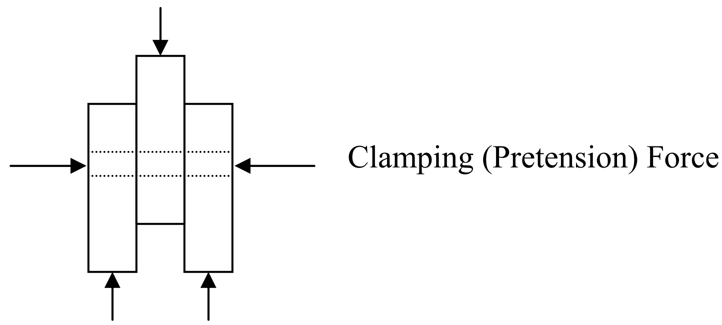
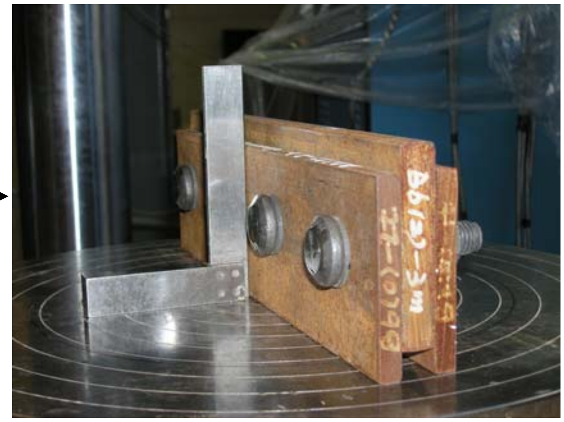


Figure 4.31 Graphic Representation of the Compression Slip Test

4.5.1 Test procedure

First, bolts were machined at the head and the tip so that they could be pretensioned in the steel joints by applying a prescribed elongation as indicated on the Bolt Gage. Then, the fasteners were positioned in the steel joints, so that they were in full bearing contact with the joint opposite to the direction of slip load, and pretensioned to 29-30 kips. Next, the specimen was placed in MTS displacement controlled loading frame. One linearly variable differential transformer (LVDT) was placed in the middle of each end of the center plate to measure displacement. To eliminate settling deformations from the displacement readings a small load of approximately 1 kip was applied before the LVDT's were set and zeroed. The specimen was then loaded at an average rate 0.002 inches of displacement per minute. The test was discontinued shortly after slip was observed. Figure 4.32 shows the testing procedure.

Three specimens were tested for each of the two categories. Since each steel joint specimen has four pretensioned bolts, the resulting slip load divided by four is equivalent to the average of four single-bolt slip tests. The mean slip coefficients were calculated as described in Appendix A, Section A3.5 of the RCSC Bolt Specification (2004).



Pretensioning

Placement in Loading Machine

Applied 1 kip Load

Activation of LVDT’s

Figure 4.32 Slip Test Procedure

For the rusted/weathered joints, each of the steel plates had been exposed to atmospheric conditions for at least 2 weeks. The blast-cleaned specimens had been blasted to a “brush-off” blast-cleaned surface finish. This surface finish is typical but not the most severe that can be specified as preparation for painting; it leaves the material free of rust, mill scale, dirt, grease and oil. This blast cleaning was performed at Tresman Steel Ltd. in Brampton, Ontario. The actual slip test for this category was performed three days after the specimens were blast-cleaned. During that period the steel plates were kept inside at room temperature and showed no visible change at the time of testing.

4.5.2 Slip Test Results and Analysis

Figure 4.33 presents the results from the slip tests for the newly blast-cleaned and rusted/weathered specimens. The plot represents the load-displacement curve for each test.

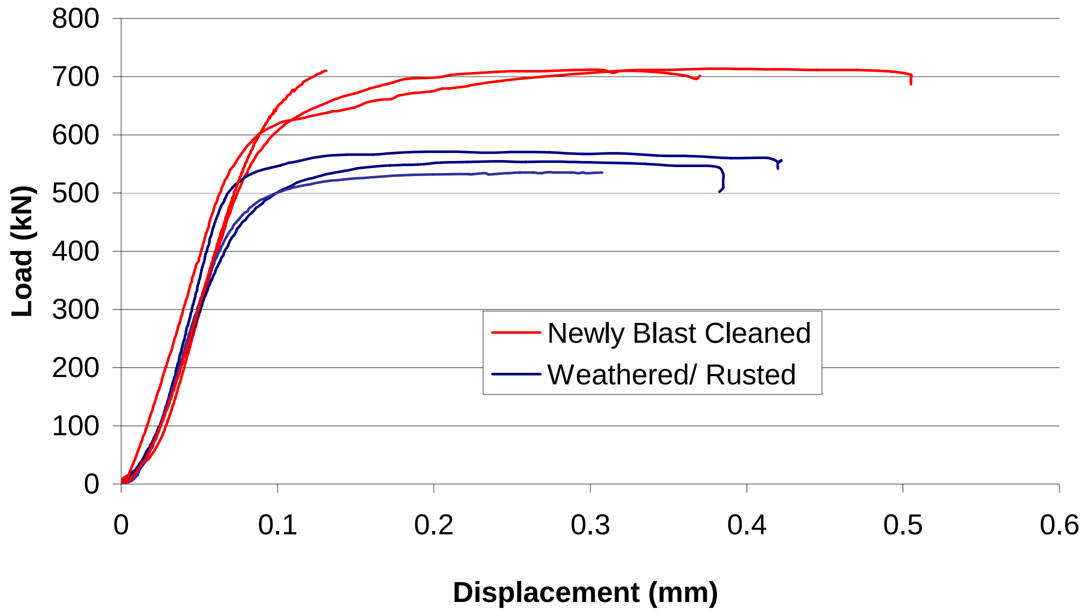


Figure 4.33 Load Displacement Curves for Blast-Cleaned vs. Weathered/ Rusted Specimens

A "bang" was heard when the slip load of the second newly blast cleaned specimen was reached. This is indicated on the graph where a rapid drop in the load is observed that corresponds to a sudden slip of the middle plate under displacement control; a report, such as this, does not always occur but is rather a function of test control, surface conditions and hole alignment.

From the graph it could be seen, that the slip load achieved in the newly blast-cleaned plates is higher than the one obtained by the weathered/rusted joints. However, all of the mean slip coefficients calculated from these slip loads exceeded the value of 0.50 recommended by the RCSC Bolt Specification. A summary of the results is presented in Table 4.22.

Table 4.22 Summary of Slip Test Results

Specimens	Avg. Slip Load (kN)	STDEV	Avg. Loss in pretension (kN)	Mean slip Coeff.	STDEV
Blast Cleaned	712	2.1	10.8	0.66	0.005
Weathered*	554	17.5	16.8	0.52	0.022

*No further cleaning or treatment was done to the weathered specimens after 4 weeks exposure before assembly

The small standard deviation in the second row of the table shows the consistent performance of the newly blast-cleaned plates. On the other hand, the weathered specimens exhibited additional scatter in the measured slip loads. The bolt tension lost during the slip movement is also listed in the table.

4.6 ROTATIONAL CAPACITY INVESTIGATION

The tension that is achieved in the twist-off installation of ASTM F1852 bolt is dependant on a host of parameters including strength of the bolt material, the geometry of the “breakneck” that is produced in manufacturer, the lubricant that is present at the time of installation and the condition of the surfaces of all contacting parts. This installation is a “torque control” technique and is one of the techniques permitted in the RCSC Specification. Once the twist-off spline has been removed, the bolt can no longer be tightened or reinstalled using the special installation wrench.

To examine the practicality of using another installation technique on the twist-off bolt, a series of tests were conducted to investigate the rotational behavior and to do direct comparisons with turn-of-nut as a reinstallation technique. The goal of these series was to determine the state of the installed fastener related to that achieved by a turn-of-nut procedure and to examine the rotational capacity of the fastener.

4.6.1 Observation of Turns during Installation of Twist-off Bolt

The purpose of this test was to compare the tension after the first installation of twist-off bolts with the tension obtained by reinstallation with the turn-of-nut method. In this way, the assembly treated as a regular bolt and tension measurement was achieved by using the Bolt Gage technique described earlier in this report.

4.6.1.1 Test procedure (measuring turn data)

First, to imitate the installation of twist-off bolts by the turn-of-nut technique, the turn involved in the twist-off tension control bolt pretensioning must be known. A sample twist-off bolt was tightened by the following procedure to determine the turn needed to shear off the splined end. The initial torque that brings the joint from contact to snug-tight condition is also required to be included in the number of turns. Only an approximate value was obtained using the Skidmore-Wilhelm calibrator, as the calibrator has typically a lower stiffness than solid steel plates of the same grip length. The twist-off bolt was tightened in the Skidmore with the same grip length as in the 3-plate joint to a load of 5 kips, and the corresponding torque indicated on the torque wrench was recorded. Then the bolt was tightened in the joint with the same amount of torque to create the same snug-tight condition. After initial tightening, match marks were made on the bolt shank and the nut to measure the relative turns between them during the continuing tightening. The bolt was then tightened with the automatic TC wrench for twist-off bolts until the splined end of the bolt was sheared off. The relative turn of the nut to bolt shank was recorded.

Another twist-off bolt was installed in the Skidmore in the same manner to record the required turn to tighten the bolt from snug-tight as well as to compare with the turn required in the steel joint installation. First the bolt was snug-tightened to a load of 5 kips. Then the splined end of the bolt was sheared off with the special wrench, and the relative turn of the nut to the bolt shank was recorded by observing the match marks.

This simulation was performed on four 3/4 in. diameter by 3 in. long twist-off bolts installed in a 3-plate joint. To employ the Bolt Gage, these twist-off bolts were machined to have flat and smooth heads and ends before installation. These bolts were then installed in a 3-plate joint proceeding systematically from the most rigid part of the joint using the turn-of-nut technique with the relative turns obtained above. First, the torque to snug-tight condition was applied with the manual dial-indicating torque wrench. Then the turn required to shear off the splined end of the bolt was applied with an electrical torque wrench, and a protractor with angular measuring marks was placed around the nut to count the relative turns of nut to bolt shank during the tightening. At the same time, the Bolt Gage was employed to record the elongations of the bolts and thus determine the pretensions achieved in the bolts.

4.6.1.2 Experimental Results and Analysis

For the twist-off bolts 3/4 in. diameter by 3 in. long it was determined that the relative turn of the nut with respect to the bolt shank required to shear off the splined end of the bolt in the steel joint was approximately 1/6 turn from snug-tight condition, while in the Skidmore it was about 1/3 turn. The pretension results of the simulated installation in the joint are shown in Table 4.23. Compared with previous pretension results of as-received bolts in Section 4.4.5 the pretensions achieved by using turn-of-nut procedure were almost the same as those obtained by the routine installation procedure for twist-off bolts.

Table 4.23 Installation of twist-off bolt by turn-of-nut method

Bolt Number (1)	L_G (in.) (2)	L_0 (in.) (3)	ΔL (in.) (4)	$T_c = K_u^0(\Delta L)$ (kips) (5)	$\frac{T_c}{T_m}$ (6)	Average (7)	Standard Deviation (8)
B-1	1.875	3.3985	0.0062	31	1.12	1.19	0.05
B-2	1.875	3.4077	0.0066	33	1.19		
B-3	1.875	3.4187	0.0069	35	1.25		
B-4	1.875	3.3985	0.0067	34	1.21		

Note: L_G = grip length; L_0 = original length of bolt without the splined end; ΔL = change in length (in.); K_u^o = calibrated bolt stiffness from direct tension test (5061 kips/in.); T_c= calibrated tension; T_m= specified minimum pretension (28 kips)

4.6.2 Rotational Capacity Test

According to ASTM A325-01, the rotational capacity test is only applicable to zinc coated bolts and zinc coated and lubricated nuts tested full size in an assembled joint or tension measure device. The purpose of the rotational capacity test as defined in ASTM A325 is to evaluate the presence of a lubricant, the efficiency of the lubricant, and the compatibility of assemblies. To investigate the reinstallation of twist-off bolts, the residual rotational capacity of the twist-off bolts reinstalled by turn-of-nut method is of interest. The rotational capacity test method stated in ASTM A325–01 was modified to examine how much reserve capacity in turns remained in the twist-off bolts installed by turn-of-nut method.

4.6.2.1 Test Procedure for Rotational Capacity Test

The rotational capacity test of twist-off bolts was conducted in the 3-plate joint to satisfy the requirements of rotational capacity test presented in ASTM A325-01. Before the bolt was placed in the joint, the splined end of the bolt was removed at the breakneck. The initial tightening of the nut should produce a load in the bolt not less than 10% of the specified proof load. Skidmore-Wilhelm calibrator and a manual dial-indicating torque wrench were used to provide enough initial loads. The bolt was first tightened in the Skidmore with the same grip length as in the joint to a load of 5~10 kips, and the corresponding torque indicated on the torque wrench was recorded. Then the bolt was tightened in the joint with the same amount of torque into snug-tight condition. After initial tightening, match marks were made on the bolt shank and the nut. The rotation required by the turn-of-nut installation method for bolts with different lengths was applied to the bolt with an electric powered torque wrench with an extended reaction arm. A multiplier was added to the torque wrench to control the tightening speed and a protractor was used to read the turns of the nut relative to the bolt shank. After 1/2 turn, the bolt then was loosened to check the acceptance as required by the ASTM A325 rotational capacity test. After the inspection of acceptance, the passed bolt was brought to snug condition again, and was tightened to failure. The rotation required to fail the bolt was recorded.

An additional rotational test for repeated installation was performed on the twist-off bolt assembly and was similar to the one described above. The only difference was that the bolt was not tightened up to failure directly after the first tightening. The bolt was retightened several times with the same rotation amount as specified in the turn-of-nut method for bolts of a given length and diameter. The number of this repeated tightening procedure up to the failure of the bolt was recorded, and the relative turns of the nut to the bolt during the final turning process was also recorded to calculate the total turns applied to fail the bolt.

4.6.2.2 Test Results from Rotational Capacity Test

The tests were conducted on three (3) assemblies from two companies. Three bolts from each manufacturer were tested. Two of them were tested for the modified rotational capacity test, and one was tested for the repeated tightening.

1. The modified rotational capacity test: two bolts with size of 3/4 in. diameter by 3 1/4 in. long from manufacturer A were first tightened with 1/2 turn as required by turn-of-nut method. After inspection of acceptance, the bolts were retightened continuously until failure. The recorded turns to bolt failure during the retightening were 1 2/3 and 1 5/6, separately. In addition, two bolts 3/4 in. diameter by 3 in. long from manufacturer B were first tightened with 1/3 turn according to the requirement of the turn-of-nut method, and the turns to fail the bolts during the second tightening were 1 1/2 and 1 7/12, separately.

2. The repeated tightening test: the bolt with size of 3/4 in. diameter by 3 1/4 in. long from manufacturer A was tightened with 1/2 turn 4 times, but it could not be loosened properly after the 4th time tightening. Thus the total turns recorded were 4 (1/2) = 2. The 3/4 in. diameter by 3 in. long assembly from manufacturer B was tightened with 1/ 3 turn 8 times, and it failed at the 9th time tightening with a 1/12 turn. Thus the total turns to fail the bolt were: 8 (1/3) + 1/12 = 2 3/4.

From the limited data shown above, the ASTM F1852 twist-off bolts that were tested have adequate rotational capacity to be reused by turn-of-nut method at least once or twice. Thus further investigation on the rotational capacity of twist-off bolts may be required to verify or broaden this conclusion.

4.7 REINSTALLATION OF REMOVED BOLTS

In the current RCSC Specification (2004), although no specific provision has been included for reuse of ASTM F1852 twist-off-type tension control bolts, but since they are largely physically equivalent to A325 one could assume that they can be treated as black ASTM A325 bolts after twisting off the spline. A limited number of bolts from each manufacturer were reinstalled using turn-of-nut method after twist-off installation and removal from the steel joints. The purpose of the reinstallation was twofold: 1. to obtain a source of base data and experience with installing a used (installed once) twist-off bolts; 2. to assess the delayed installation parameters on the turn-of-nut method and thus determine the effect of the weathering exposure on the overall behavior of the F1852 fastener assembly. The only difficulty in this procedure is that without a hex head on the bolt, backup of the bolt may require some less conventional head restraint at the beginning of tensioning.

4.7.1 Reinstallation Test Procedure

The removed bolt was first snug-tightened in the 3-plate joint with full effort to about 5 to 10 kips tension using a regular spud wrench. A match mark was drawn both on the bolt and on the nut to count the relative rotation of the nut to the bolt after tightening. The nut was then turned to the required rotation. For bolts of length larger than 4d (nominal bolt diameter), a half turn is required; for bolts with length less than or equal to 4d, a third turn was required. After turn-of-nut pretensioning, the Bolt Gage was mounted to measure the change in bolt length during the nut loosening process. With the transducer remaining on the bolt head, the nut was again loosened with a dial-indicating torque wrench.

4.7.2 Results of TC Bolt Reinstallation with Turn-of-Nut Method

Reinstallation tests were performed both in the preliminary test period and also in the subsequent tests for bolts from four companies. The test results are all reported in Table 4.24 below for comparison. It can be seen that reinstallation of ASTM F1852 TC bolts with turn-of-nut method achieved higher pretension than twist-off pretensioning for bolts from all four companies. There was no apparent increase in bolt pretension for bolts turned with 1/2 turn as compared to those turned with 1/3 turn.

Table 4.24 Results from twist-off installation and turn-of-nut reinstallation

Bolt Size (Manufacturer) (1)	Twist-off installation					Turn-of-nut reinstallation					
	ΔL (in.) (3)	$T_c = K_u^0(\Delta L)$ (kips) (4)	T_c / T_m (5)	Average (6)	STDEV (7)	Turns (8)	ΔL (in.) (9)	$T_c = K_u^0(\Delta L)$ (kips) (10)	T_c / T_m (11)	Average (12)	STDEV (13)
Φ 3/4" x 3 1/4" (A)	0.0060	29.2	1.04	1.06	0.02	1/2	0.0092	44.5	1.59	1.58	0.01
	0.0061	29.7	1.06				0.0091	44.1	1.57		
	0.0062	30.1	1.08				0.0091	44.3	1.58		
Φ 3/4" x 3" (B)	0.0065	32.9	1.17	1.17	0.04	1/3	0.0085	42.8	1.53	1.56	0.04
	0.0063	31.9	1.14				0.0086	43.4	1.55		
	0.0067	33.9	1.21				0.0088	44.7	1.60		
Φ 3/4" x 2 3/4" (C)	0.0060	33.9	1.21	1.19	0.02	1/3	0.0074	41.8	1.49	1.57	0.07
	0.0058	32.8	1.17				0.0079	44.6	1.59		
	0.0059	33.3	1.19				0.0081	45.8	1.63		
Φ 3/4" x 2 3/4" (D)	0.0056	31.5	1.13	1.17	0.05	1/3	0.0074	41.6	1.49	1.54	0.06
	0.0061	34.3	1.23				0.0080	45.0	1.61		
	0.0058	32.6	1.17				0.0076	42.8	1.53		

Note: ΔL = change in bolt length during nut loosening; T_c = calibrated tension; K_u^o = calibrated bolt stiffness from direct tension test; T_m = specified minimum pretension (28 kips); Turns= number of turns after snug tight condition

Figure 4.34 on the next page presents a comparison of the pretensions achieved by the twist-off installation and turn-of-nut reinstallation from the four companies combined. It can be seen that the preloads obtained by the turn-of-nut method on TC bolts are much higher than those from the initial twist-off installation. In addition, the results from the former have a smaller standard deviation which can also be observed in the figure. These results suggest that the turn-of-nut reinstallation is a reliable alternative method for achieving the required pretension in twist-off type tension control assemblies. Test results for exposed fastener assemblies have not been completed.

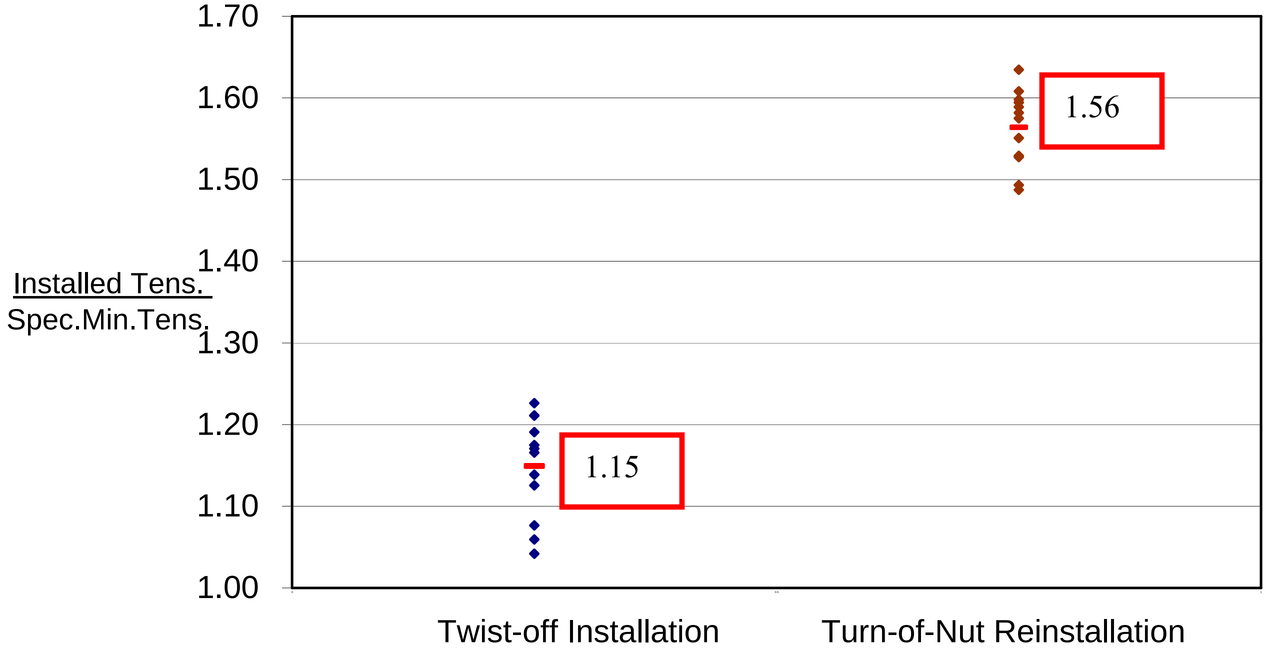


Figure 4.34 Comparison between twist-off installation and turn-of-nut reinstallation of as-received TC bolt assemblies

4.8 COMPARISON OF BOLT GAGE AND SKIDMORE LOAD RESULTS

Skidmore-Wilhelm calibrator is a hydraulic calibrator for bolts and is most frequently used in structural work. The instrument shows the actual tension achieved in the fastener after the fastener is mounted and tightened in the calibrator. Since the stiffness of the hydraulic cylinder is much less than the stiffness of the actual solid steel joint, the tension recorded by the calibration versus the Bolt Gage are examined from the aspect of tension determination and from interaction of the stiffness of the Skidmore with the tightening operation.

As shown in the previous sections, the bolt tension results from the Skidmore verification tended to be higher than those installed tension in the steel joint that was determined by the Bolt Gage. To examine the variation of the tension results from the Skidmore and the Bolt Gage, several tests were performed and different approaches were used to compare the tension results from these two bolt tension measurement methods.

4.8.1 Skidmore-Wilhelm Torque-Tension Test

To monitor the bolt torque-tension loading and unloading process in the Skidmore-Wilhelm calibrator, as well as to compare the tension results from the Bolt Gage and the Skidmore, a 3/ 4 in. diameter by 3 1/4 in. long bolt from Company A was tightened and then loosened in the Skidmore twice. Before the bolt was mounted in the Skidmore, it had been prepared to have smooth and flat surfaces at the head and the end to engage the Bolt Gage. The bolt was tightened up to 28 kips at several regular load steps and then loosened at the same load steps as in the tightening process using a dial-indicating manual torque wrench. The bolt elongation at each load step was recorded.

Figure 4.35 presents the Skidmore load vs. Bolt Gage elongation relationship during the bolt tightening and loosening process. The lines which connected those points at different load steps in the loading or unloading process were slightly nonlinear, and the slopes of the lines were almost the same.

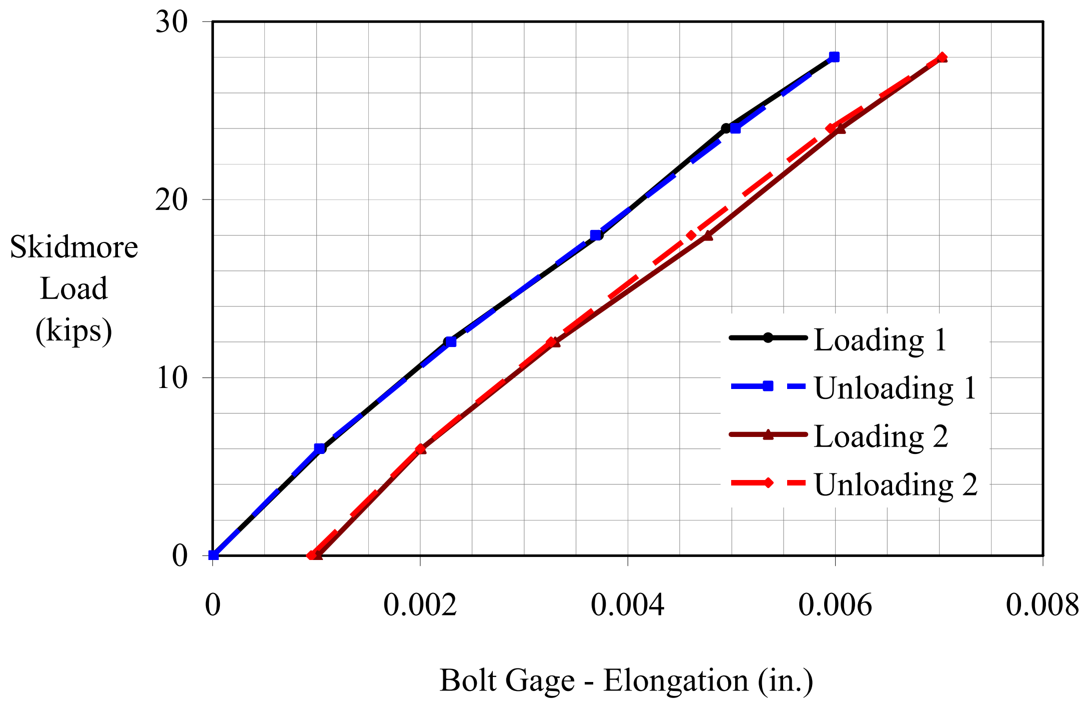


Figure 4.35 Skidmore load vs. Bolt Gage elongation for torque- tension loading

Figure 4.36 gives the comparison between the calibrated bolt tension from the Bolt Gage and the Skidmore load when the bolt was tightened and loosened using the manual torque wrench in the Skidmore. At each load point the calibrated tension from the Bolt Gage was close to the tension from Skidmore. At a typical pretension of 28 kips the Skidmore tension is about 1 kip more than the bolt gage.

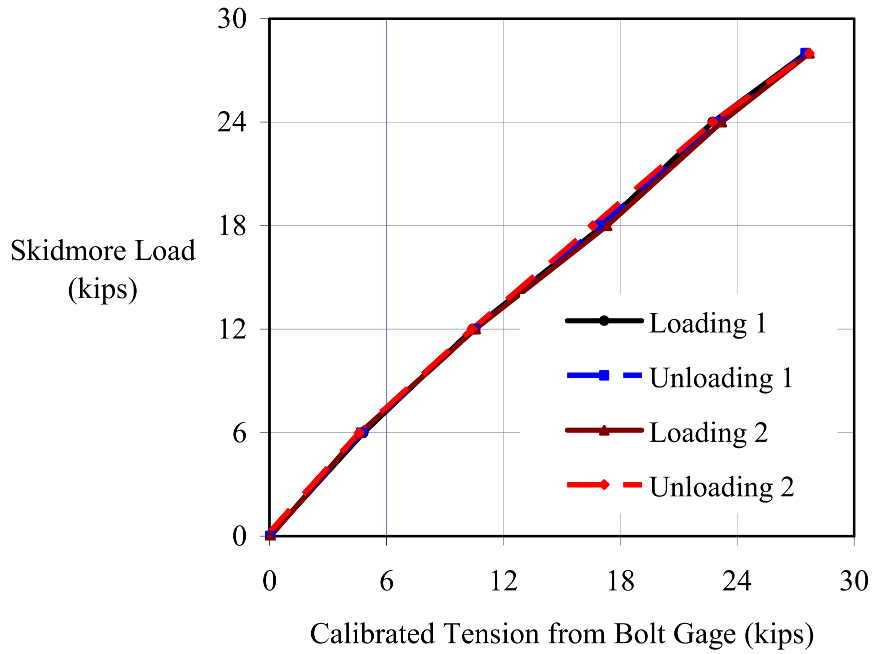


Figure 4.36 Skidmore load vs. calibrated tension from the Bolt Gage

4.8.2 Skidmore-Wilhelm TC Bolt Twist-off Installation Test

To further investigate the variation of tension results from the Bolt Gage and the Skidmore validation tests, the twist-off bolts were installed in the Skidmore calibrator with the automatic TC wrench, and after the installation the Bolt Gage was applied on the bolt to establish the pretension during the unloading process. The tension results from Skidmore were also used to compare with the pretension results for bolts installed in the 3-plate joints.

4.8.2.3 Test Procedure for Comparison of Bolt Gage and Skidmore Load Results

To compare the bolt pretension achieved in the Skidmore twist-off installation with those calibrated tension from the Bolt Gage in the steel joint twist off installation, the bolts were installed in the Skidmore device with the same grip length as provided by the 3-plate joint. Three bolts from each of the two companies (A and B) were tested by the steps described below.

Before the bolt was installed in the Skidmore-Wilhelm bolt tension calibrator with the automatic TC wrench, the head of the bolt was ground flat and smooth to accommodate the magnetic transducer of the Bolt Gage. The bolt was first tightened in the Skidmore to a snug-tight condition; this corresponded to a tension of about 5 to 10 kips as indicated on the Skidmore. The splined end of the bolt was sheared off with a rough surface upon installation. This rough tip was also ground flat and smooth to measure the length of the bolt with the Bolt Gage. Before the reading from the Skidmore was recorded, the oil pressure gage was tapped to minimize the dial friction.

After bolt installation, the Bolt Gage was engaged to measure the initial elongated length of the bolt. The bolt was then loosened with a manual dial-indicating torque wrench, and the maximum loosening torque reached was showed on the dial. To detect anything abnormal that may have happened during the procedure the torque value was checked to see that it was in the normal range and assure that the bolt remained elastic during the unloading. In addition, during the unloading procedure, the changes of the bolt length were measured and recorded at several load points to gather data for further data to evaluate the linearity of the release.

4.8.2.4 Comparison of Bolt Gage and Skidmore tensions

The results of the test are summarized in Table 4.25 and Table 4.26.

Bolts from two companies A and B were tested for comparison. From Table 4.25, the installed tension from the Skidmore was only about 1% higher than the calibrated tension from the Bolt Gage on average. For bolts from these two companies, the average achieved tensions in this Skidmore installation were very close to the tension results from the pre-installation verification tests of the as-received bolts as shown in Section 4.4.5, while they were all higher than those installed tensions in the steel joints.

Table 4.25 Comparison results between calibrated bolt tension and the tension from Skidmore-Wilhelm bolt tension calibrator

Bolt Number (1)	D (in.) (2)	L (in.) (3)	L_0 (in.) (4)	L_G (in.) (5)	ΔL (in.) (6)	T_s (kips) (7)	$T_c = K_u^o\ (\Delta L)$ (kips) (8)	Δ (%) (9)	Torque (ft-lbs) (10)
A-1	3/4	3 1/4	3.806	2.000	-0.0065	32.5	31.6	-3	230
A-2	3/4	3 1/4	3.793	2.000	-0.0065	32.0	31.6	-1	235
A-3	3/4	3 1/4	3.773	2.000	-0.0064	31.0	31.1	0	235
B-1	3/4	3	3.441	1.875	-0.0073	38.0	36.9	-3	220
B-2	3/4	3	3.466	1.875	-0.0063	32.0	31.9	0	215
B-3	3/4	3	3.438	1.875	-0.0072	36.0	36.4	1	210

Note: D = nominal diameter of bolt; L = nominal length of bolt; L_0 = elongated length of bolt without the splined end; L_G = grip length; ΔL = change in bolt length during nut loosening; T_s = tension from Skidmore; T_c = calibrated tension; K_u^o = calibrated bolt stiffness from direct tension test

Table 4.26 Bolt stiffness calibration for torqued tension in the Skidmore

Bolt # (1)	Ts (kips) (2)	Elongation (in.) (unloading) 30 kips (3)	25 kips (4)	20 kips (5)	15 kips (6)	10 kips (7)	5 kips (8)	0 kips (9)	Regression Analysis K_u^o (kips/in) (10)	R Square (11)
A-1	32.5	-	0.0015	0.0025	0.0034	0.0043	0.0054	0.0065	4937	0.998
A-2	32.0	-	0.0016	0.0025	0.0036	0.0045	0.0055	0.0065		
A-3	31.0	-	0.0013	0.0023	0.0033	0.0043	0.0053	0.0064		
B-1	38.0	0.0016	0.0026	0.0035	0.0044	0.0052	0.0062	0.0073	5170	0.999
B-2	32.5	-	0.0015	0.0025	0.0034	0.0043	0.0053	0.0063		
B-3	36.5	0.0014	0.0023	0.0033	0.0043	0.0052	0.0062	0.0072		

Note: T_s = tension from Skidmore; K_u^o = calibrated stiffness of bolt from torque- tension loading.

Further, from Table 4.26, the average values of calibrated bolt stiffness from this torqued tension test for these two kinds of bolts were 4937 kips/in. and 5170 kips/in., while correspondingly the calibrated bolt stiffness from direct tension test were 4862 kips/in. and 5061 kips/in. The difference between the stiffnesses that were calculated from direct tension calibration and Skidmore torque tension calibration was also only about 1~2%. Theoretically, during torque tensioning of a bolt, as the turns were applied to the nut, the number of threads in the grip was getting smaller and thus resulted in a small gradual increase in the bolt stiffness. As described in Section 4.6.2.2, more turns from snug were applied to the nut during the Skidmore installation than in the steel joint installation. Thus, the variation of bolt stiffness during the Skidmore installation would be more apparent than during the steel installation. From the test results shown above, it can be concluded that the variation of bolt stiffness during the steel joint installation is negligible.

Seen from above, the tension results from these two bolt tension calibration methods (the Bolt Gage technique and the Skidmore calibrator) were very close in the above two tests. To further verify the comparison results from the above tests, a strain gaged bolt was used as a demonstration.

4.9 BOLT WITH STRAIN GAGES- LOAD VERIFICATION

An additional method of measuring bolt load is to apply strain gages to the shank of the bolt and create a built-in load transducer. There are two main purposes for this test. One is to compare the pretensions gained from the Bolt Gage, the Skidmore-Wilhelm calibrator, and the strain gages. The other is to observe the relaxation or loss of bolt load after installation. Using a strain gaged bolt is also considered to be an accurate way for monitoring short term relaxation and initial pretension.

4.9.1 Strain Instrumentation

The target bolt was of size 3/4 in. diameter by 3 in. long. The bolt shank was machined flat at two opposite location right under the bolt head into two smooth surfaces paralleled to the bolt shank. As shown in Figure 4.37, the cut area is about 10mm wide (W) x 20mm long (L), which should be as small as possible. Two 2 mm holes positioned at the middle points of the widths of these two machined areas on the bolt shank were drilled through the bolt head and directed slightly inclined to the edge of the head. In addition, to accommodate the transducer of the Bolt Gage, the head of the bolt was machine ground to a flat and smooth surface; this area should be big enough for the magnetically held transducer. Lastly, the splined end of the bolt was removed at the groove. The amount of material cut from the bolt head and shank was minimized. During this preparatory procedure the threads of the bolt were protected with a plastic wrap to preserve the as-received condition of the thread.

Two pairs of 2 mm long strain gages were separately mounted on the two flat areas on the bolt shank. One gage was placed parallel to the bolt shank to measure the axial strain directly, while the other one placed perpendicularly worked as a dummy gage for temperature compensation. The four gages thus formed a full Wheatstone bridge connection, and the output of the strain indicator was a strain reading proportional to axial load while compensating for any induced bending effects.

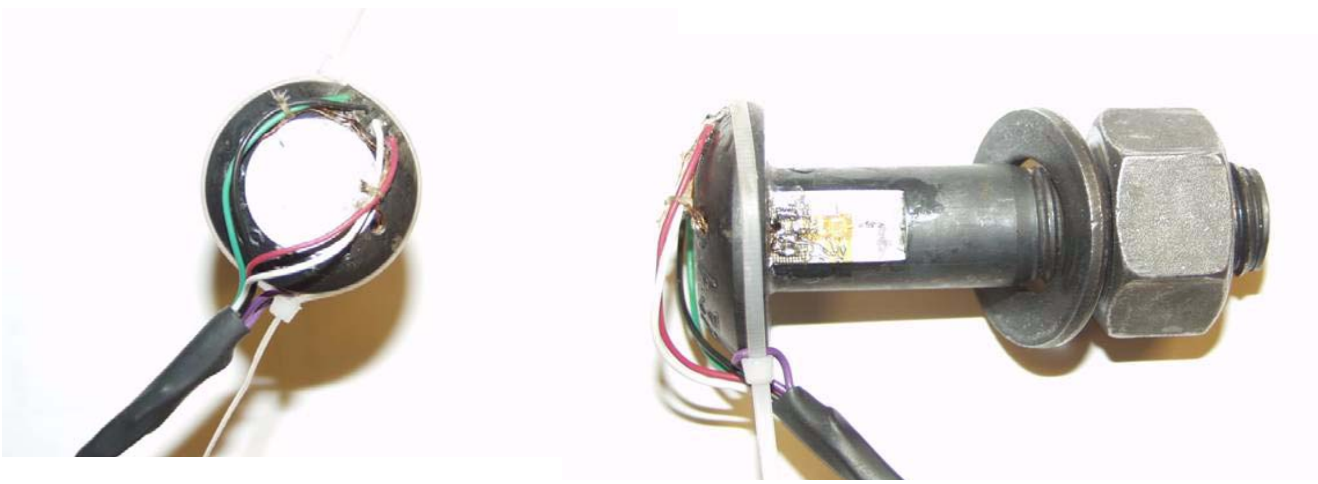


Figure 4.37 Strain gaged bolt

4.9.2 Experimental Procedure for Load Verification with the Strain Gaged Bolt

Before any meaningful data could be obtained from the strains, the bolt with strain gages system were calibrated. The bolt was placed in a tensile testing adapter shown in Figure 4.4 with the same grip length of 1.875 in. as found in the 3-plate joint. The tensile testing adapter was then loaded up to the proof load (28 kips) of the bolt by a universal testing machine with 120 kips capacity. The outputs of the strain indicator were recorded at several load points at a regular load step interval. At the same time, the Bolt Gage was also used to obtain the bolt elongations at the same load points. The tensile testing adapter was then unloaded at the same load points as in the loading path. The same loading and unloading procedure were then repeated 2 times but with a different grip length each time. One was 1/3 turn shorter than the original grip, another was 1/2 turn shorter than the original grip. During each loading cycle, at each load step a calibration factor was calculated. The average value of all the calculated factors was taken as the final strain gage calibration factor that will be used for further bolt pretension calibration.

Some bolt tension calibration tests were carried out after the calibration factor was obtained. First, this strain gaged bolt was used to calibrate the Skidmore-Wilhelm bolt tension calibrator. The bolt was inserted in the Skidmore with a grip length of 1.875 inch. The Bolt Gage was also used to compare the results. The strain gaged bolt was tightened with a dial-indicating wrench up to about 25 kips at several load steps and then unloaded step by step. At each load step, the readings from Skidmore, the Bolt gage and the strain gage indicator were all recorded.

Second, the strain gaged bolt was tightened in the Skidmore-Wilhelm calibrator to examine the relaxation effect; the Bolt Gage was used. Because of the indentation of the small plate on the Skidmore, several washers were put under the head of the bolt to accommodate the transducer of the Bolt Gage. After the Bolt Gage was mounted and the initial length of the bolt was recorded by the Bolt Gage, the bolt was first tightened to a snug-tight condition, and then tightened with an electrical torque wrench using a multiplier to enable slowly applied rotation and tension. The tightening was stopped at 33.2 kips, which was read directly from Skidmore-Wilhelm calibrator. Before any reading was recorded from the Skidmore-Wilhelm calibrator, a few taps on the meter were employed to minimize the dial friction; the size of the dial and needle indicator suggests that reading be no closer than 0.2 to 0.5 of the interval. The outputs of the strain indicator as well as the Bolt Gage were also recorded. The bolt was then left there for 5 hours for further observation. The data were recorded as above at convenient time intervals to examine the relaxation of the bolt.

Finally, the strain gaged bolt was tested in the 3-plate joint. The strain gaged bolt was placed at the fourth tightening position in the joint, together with 3 other regular bolts being tightened to snug-tight condition. After the initial length of the bolt was recorded, the strain gaged bolt was tightened with an electrical torque wrench from snug-tight condition. A multiplier was added to control the load application speed, while the tightening procedure was monitored by the Bolt Gage. The tightening was stopped at $\Delta L = 0.0066$ in.; this is the regular elongation value after bolt installation.

The reading from the strain indicator was recorded immediately. Before the bolt was released, the monitoring procedure had lasted for 5 hours. During this process, both the readings from the Bolt Gage and the strain indicator were recorded at various times.

4.9.3 Determination of the Strain Gage Calibration Factor and Bolt Stiffness

The calibration factor is calculated from the measured strain output in the form of a voltage and applied load indicated on the bolt testing device.

$$K_c = \frac{T_m}{\varepsilon_{output}} \tag{4.1}$$

where,

K_c = calibration factor

T_m = bolt tension from testing device

ε_{output} = output from strain gages on the bolt in

The strain gaged bolt was loaded and unloaded 3 times in direct tension. The average strain gage calibration factor obtained through the test procedure describe above was 5.23 x 10^{-3} kips/μstrain This factor was then used to relate the strain gage output to the bolt tension. Therefore, the calibrated bolt tension from the strain gages, T_G, can be calculated as follows:

$$T_G = K_c\left(\varepsilon_{output}\right) \tag{4.2}$$

The stiffness of the bolt was calculated from the linear regression analysis of bolt elongation data from the Bolt Gage and the tension data from the loading machine. Regression analysis had been performed on the 3 loading cycles. In each loading cycle, the slopes and Y-intercepts of tension-elongation curve for loading, unloading, and combined loading and unloading data group were calculated separately for comparison, see Table 4.27. It was found that with 1/3 turn shorter of threads in grip the variation of calibrated stiffness was about 2% and after 1/2 turn the variation was about 3%. This agreed well with the theoretical bolt stiffness analysis as shown in Table 4.28.

Table 4.27 Strain gaged bolt stiffness calibration results

Loading Cycle	Loading			Unloading				
	K, Stiffness	Y-intercept	R square	K_u, Stiffness	Y-intercept	R square	K_u^o, Stiffness	R square
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	4996	0.00	1.000	5041	-0.23	1.000	4983	0.999
2 (1/3 turn)	5075	0.17	1.000	5142	-0.20	1.000	5089	1.000
3 (1/2 turn)	5172	0.05	0.999	5209	-0.24	1.000	5146	1.000

Note: K =average bolt stiffness obtained from linear regression analysis of combined loading data; K_u = average bolt stiffness obtained from linear regression analysis of combined unloading data; K_u^o = average bolt stiffness obtained from linear regression analysis of combined unloading data with the best fit line being forced through the origin.

Table 4.28 Theoretical bolt stiffness variations with different threads in grip

Bolt Size	original grip length			after 1/3 turn				after 1/2 turn			
	L_G (in.)	L_{Se} (in.)	K_{t_0} (kips/in.)	L_G (in.)	L_{Se} (in.)	K_t (kips/in.)	$\Delta K_t/k_{t0}$ (%)	L_G (in.)	L_{Se} (in.)	K_t (kips/in.)	$\Delta K_t/K_{t_0}$ (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
ϕ 3/4 x 2 1/2	1.250	0.71	6634	1.217	0.68	6783	-2.2	1.200	0.66	6861	-3.4
ϕ 3/4 x 2 3/4	1.625	0.80	5513	1.592	0.77	5608	-1.7	1.575	0.75	5661	-2.7
ϕ 3/4 x 3	1.875	0.76	5019	1.842	0.73	5104	-1.7	1.825	0.71	5148	-2.6
ϕ 3/4 x 3 1/4	2.000	0.70	4829	1.967	0.67	4908	-1.6	1.950	0.65	4948	-2.5
ϕ 3/4 x 3 1/4	2.250	0.95	4310	2.217	0.92	4373	-1.5	2.200	0.90	4405	-2.2

Note: L_G = grip length; L_{Se} = effective length of exposed threads; K_{t_0} = calculated bolt stiffness with original grip length; $\Delta K_t/K_{t_0}$ = the variation of K_t expressed as a percentage of K_{t_0} (K_{t_0} and K_t were calculated using Equation (3.4) and Equation (3.5))

4.9.4 The Skidmore-Wilhelm Calibration Results

Shown in Figure 4.38 and Table 4.29, the tension results from the Skidmore, the Bolt Gage, and the strain gage indicator agree well to 25 kips.

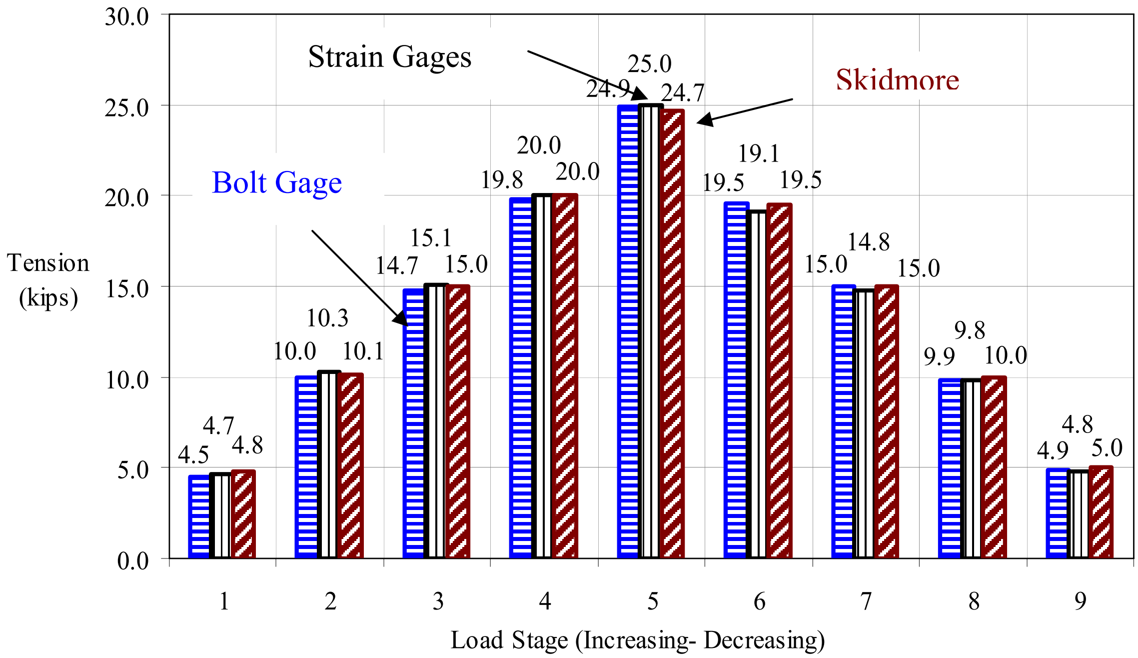


Figure 4.38 Comparison of tension results from the Bolt Gage, the strain gages and the Skidmore-Wilhelm calibrator

Table 4.29 Tension results of strain gaged bolt installed in the Skidmore

Loading Path (1)	Bolt Gage: ΔL (in.) (2)	Bolt Gage: $T_C = K_u(\Delta L)+Y$ (kips) (3)	Strain Gage: ε_{output} ($\mu\varepsilon$) (4)	Strain Gage: $T_G = K_c(\varepsilon_{output})$ (kips) (6)	Skidmore: T_S (%) (7)
loading	0.00093	4.5	892	4.7	4.8
	0.00202	10.0	1962	10.3	10.1
	0.00297	14.7	2882	15.1	15.0
	0.00398	19.8	3833	20.0	20.0
	0.00499	24.9	4778	25.0	24.7
unloading	0.00392	19.5	3661	19.1	19.5
	0.00302	15.0	2821	14.8	15.0
	0.00200	9.9	1877	9.8	10.0
	0.00101	4.9	917	4.8	5.0

Note: ΔL = measured elongation of bolt from Bolt Gage; K_u = bolt stiffness from direct tension calibration (5041 kips/in.); Y = Y-intercept from direct tension calibration (-0.2 kips); T_C = calibrated tension from Bolt Gage; K_c= calibration factor for the strain gage; ε_{output} = strain gage reading; T_G = calibrated tension from strain gage; T_S = tension from Skidmore.

It can be seen from Figure 4.38 that the three load indicating techniques consistently agreed with one another. The maximum difference between the Skidmore and the Bolt Gage was only 0.3 kips; this is close to the close to the resolution that can be achieved with direct reading of the Skidmore.

4.9.5 Relaxation Investigation Results and Analysis

The test results of the bolt tension relaxation for the strain gaged bolt installed in the 3-plate joint are shown in Table 4.30 and Figure 4.39.

Table 4.30 Load relaxation data for bolt installed in the 3-Plate joint

Time	Bolt Gage		Strain Gage	
	ΔL	$T_C = K_u(\Delta L)+Y$	ε_{output}	$T_G = K_c(\varepsilon_{output})$
(min.)	(in.)	(kips)	($\mu\varepsilon$)	(kips)
(1)	(2)	(3)	(4)	(6)
0	0.00660	33.0	6365	33.3
1	0.00650	32.5	6320	33.1
2	0.00645	32.3	6302	33.0
3	0.00643	32.2	6288	32.9
6	0.00642	32.1	6270	32.8
10	0.00642	32.1	6266	32.8
15	0.00642	32.1	6254	32.7
30	0.00642	32.1	6254	32.7
60	0.00641	32.1	6254	32.7
120	0.00641	32.1	6254	32.7
180	0.00641	32.1	6250	32.7
240	0.00641	32.1	6250	32.7
300	0.00641	32.1	6250	32.7

Note: ΔL = measured elongation of bolt from Bolt Gage; T_C = calibrated tension from Bolt Gage; K_u= bolt stiffness from direct tension calibration (5041 kips/in.); Y= Y-intercept from direct tension calibration (0.2 kips); K_c= calibration factor for the strain gage; ε_{output} = strain gage reading; T_G = calibrated tension from strain gage;

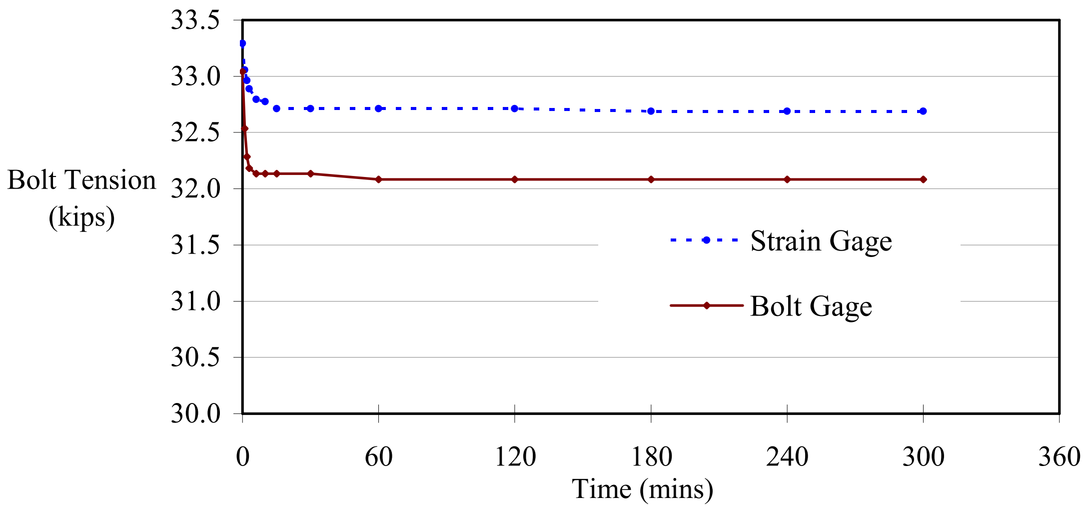


Figure 4.39 Relaxation of bolt installed in the 3-plate joint shown as a function of time

For both readings, the relaxation of the bolt occurred mainly in the first 10 to 15 minutes after the installation. From the Bolt Gage and the strain gage indicator, the amount of the relaxation is seen to be about 3% of the pretension. However, no change in tension can be observed from Skidmore-Wilhelm calibrator dial after the friction of the movement was eliminated by a few taps on the meter. The relaxation rate finally approached zero as indicated by the data read from the Bolt Gage and the strain indicator.

Also as shown in the graph, the pretensions obtained from the Bolt Gage are lower than those from the strain gages by 1~2%; this is considered good agreement. Since the strain gage is recognized as an accurate tool for measuring strains, from the results achieved above, one can conclude that use of Bolt Gage for the measurement of bolt pretension is effective, and accurate. Use of the Bolt Gage is more efficient and economical.

4.10 ELASTIC INTERACTION EFFECT INVESTIGATION

The majority of the bolt pretension data reported in this paper was obtained from bolts installed in the four bolts 3-plate joint specifically designed for those test categories cited previously. To achieve final bolt tensions with a smaller scatter, the joint was snugged first and the bolts were tightened from the center of the bolt pattern toward the edge. Even so, the elastic interactions between bolts may still exist and affect the residual preloads in the bolts. To examine the loss of initial preload in the bolts as a result of elastic interaction, the following test was carried out. The use of the Bolt Gage that is an ultrasonic measurement device made it possible to check the elastic interactions during the tightening process.

4.10.1 Test Procedure for Interaction

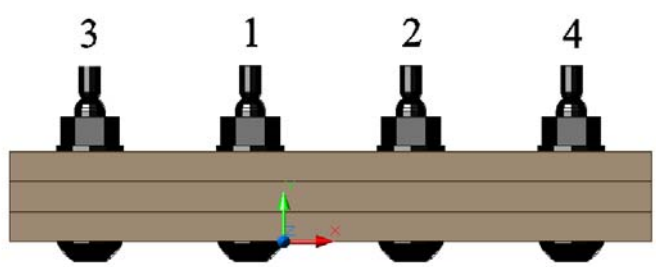
The 3-plate joint shown in Figure 4.13 was first brought into a snug condition. The tightening procedure was illustrated as the numbering of the bolts in the picture shown in Table 4.31. The bolt was tightened with the automatic TC wrench. After the first bolt was tightened, the head and the end of this bolt were ground flat and smooth to measure the bolt length by the Bolt Gage. The initial stretched length of the first bolt was recorded by the Bolt Gage, and the magnetic transducer of the Bolt Gage was left on this bolt to monitor the changes of the bolt length during the subsequent tightening of the remaining bolts.

4.10.2 Elastic Interaction Effect Observation

The bolts of size 3/4 in. diameter by 3 1/4 in. long from manufacturer A were tested in 3-plate joint. The test results were shown in Table 4.31.

Table 4.31 Results of interaction effect investigation test

Tightening Process (1)	L (in.) (2)	ΔL (in.) (3)	$\Delta T_c = K_u^o\ (\Delta L)$ (kips) (4)
1	3.7750	0	0
2		0.00003	0.1
3		0.00004	0.2
4		0.00003	0.1



Note: L = initial stretched length of the first bolt; ΔL = change in bolt length; K_u^o = calibrated bolt stiffness from direct tension test (4862 kips/in.); ΔT_c = change in bolt calibrated tension.

The data in Table 4.31 shows that the tightening of the second bolt had a relatively insignificant effect on the pretension of the first tightened bolt, and the tightening of the third and fourth bolt in the process did not affect the pretension in the first bolt. The resolution of the Bolt Gage was about 1/10000 in., while the changes in the initial stretched length of the first bolt during the tightening procedure observed from the Bolt Gage were at the level of 1/100000 in. It can be concluded that the elastic interactions between bolts was negligible in this four bolt 3-plate joint.

4.11 INVESTIGATION OF BOLT HEAD PREPARATION

The Bolt Gage technique was used in this project to evaluate the TC bolt pretension in the steel joint. To engage the transducer of the Bolt Gage, the head of the bolt and the end of bolt were ground to two parallel smooth and flat surfaces after the bolt installation. During the grinding some material was taken off bolt head because of the button style head shape. The amount of material that was removed from the bolt head should be minimized when using the Bolt Gage technique to prevent load loss as a result of material removal before measurement.

Some tests were performed to examine the effect of the removal of the bolt head material on bolt pretension. First, several groups of bolts with different amount of material removed from the bolt head were installed in the steel joints and then tested in direct tension using the MTS machine to determine the bolt stiffness. Secondly, a group of TC bolts were installed in the steel joints directly without head removal. After installation the head and the end of the bolts were ground to engage the Bolt Gage. The tension results from tests with bolt head grinding before and after installation were compared. Thirdly, the grinding effect was examined with bolts that were installed in the Skidmore directly.

4.11.1 Calibrated Tensions for Bolts with Various Amount of Head Material Removal

The height of the bolt head is a factor that may affect the stiffness of the bolt assembly. The effect of the height of the bolt head on the bolt stiffness was examined with direct tension calibration test in laboratory. The target ϕ 3/4” x 3 1/4” bolt of this test program was from Manufacturer A. Several groups of bolts with different amount of material removed from the head before or after the installation were tested and the calibrated tension results were compared. The grip length of bolts in each group was 2 inches.

4.11.2 Test Procedure for Investigation of Bolt Head Preparation Effect

Before the determination of the various bolt head heights to be examined, the geometrical shape of the bolt head was determined. Figure 4.40 shows the detail. Three bolts from the same lot were measured with the micrometer calipers. The dimensions shown in Figure 4.40 were the average readings of three bolts.

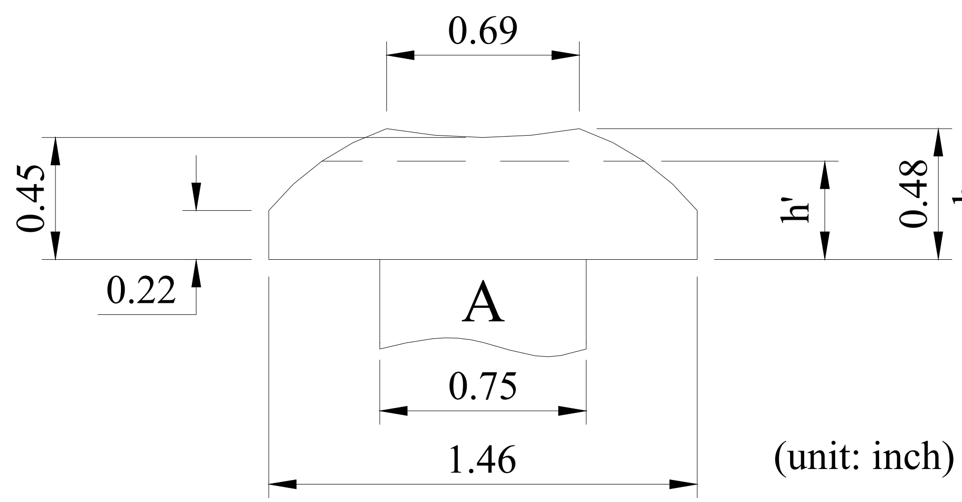


Figure 4.40 Details of the bolt head (ϕ 3/4” x 3 1/4” bolt from Manufacturer A)

Four groups of bolts (4 bolts per group) were machined to have 4 different head heights. Before the bolt heads were machined, the bolt threads were wrapped with plastic sheet to protect the bolt lubrication and thread surfaces. The whole bolt assembly was marked for identification. The washer and nut were taken off the bolt assembly and properly stored.

Each group of bolts (4 bolts) were installed in the 3-plate steel joint with the automatic TC wrench. Then the tips of the bolts were manually ground. The Bolt Gage was engaged to determine the bolt elongation during the nut loosening. The nut was loosened with a dial indicating torque wrench. The bolt elongations were recorded to evaluate the bolt pretensions after the bolt stiffness was determined with the direct tension calibration.

In addition, a group of bolts (12 bolts) were first installed in the 3-plate joints with the automatic TC wrench, and then were manually ground on the head and the end of bolt to engage the Bolt Gage. The bolt elongation was recorded by the Bolt Gage during the nut loosening. The nut was loosened using a dial indicating torque wrench.

The bolt assemblies were then placed in the tensile bolt testing adapter and loaded in direct tension in the MTS machine to calibrate and determine the bolt stiffness. The Bolt Gage was used to record the bolt elongation at several regular load steps both during the loading and unloading processes.

4.11.3 Analysis of Test Results and Comparisons

The bolt stiffness calibration results of Φ 3/4” x 3 1/4” bolt (A) with 2” in grip were shown in Table 4.32, and the stiffness comparisons of bolts with various amount of head material removal can be seen clearly in Figure 4.41.

Table 4.32 Stiffness calibration results of bolts with various head heights

Bolt group #	h', head height (after grinding) (in.)	(1 - h' / h) x100 (percentage of head removal)	Bolt sample size	$T_c = K_u (\Delta L) + Y$			$T_c = K_u^o (\Delta L)$	
				K_u (kips/in.)	Y-intercept (kips)	R square	K_u^o (kips/in.)	R square
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	0.44	10	3	4796	0.2	1.000	4853	1.000
2	0.42	14	3	4942	0.3	0.999	5021	0.999
3	0.39	20	3	5030	-0.2	0.998	4990	0.998
4	0.34	31	3	4975	0.2	0.999	5032	0.999
5	0.29	41	3	5001	-0.1	0.998	4978	0.998

Note: h = original bolt head height; h’ = bolt head height after grinding; K_u = average bolt stiffness obtained from linear regression analysis of combined unloading data; K_u^o = average bolt stiffness obtained from linear regression analysis of combined unloading data with the best fit line being forced through the origin.

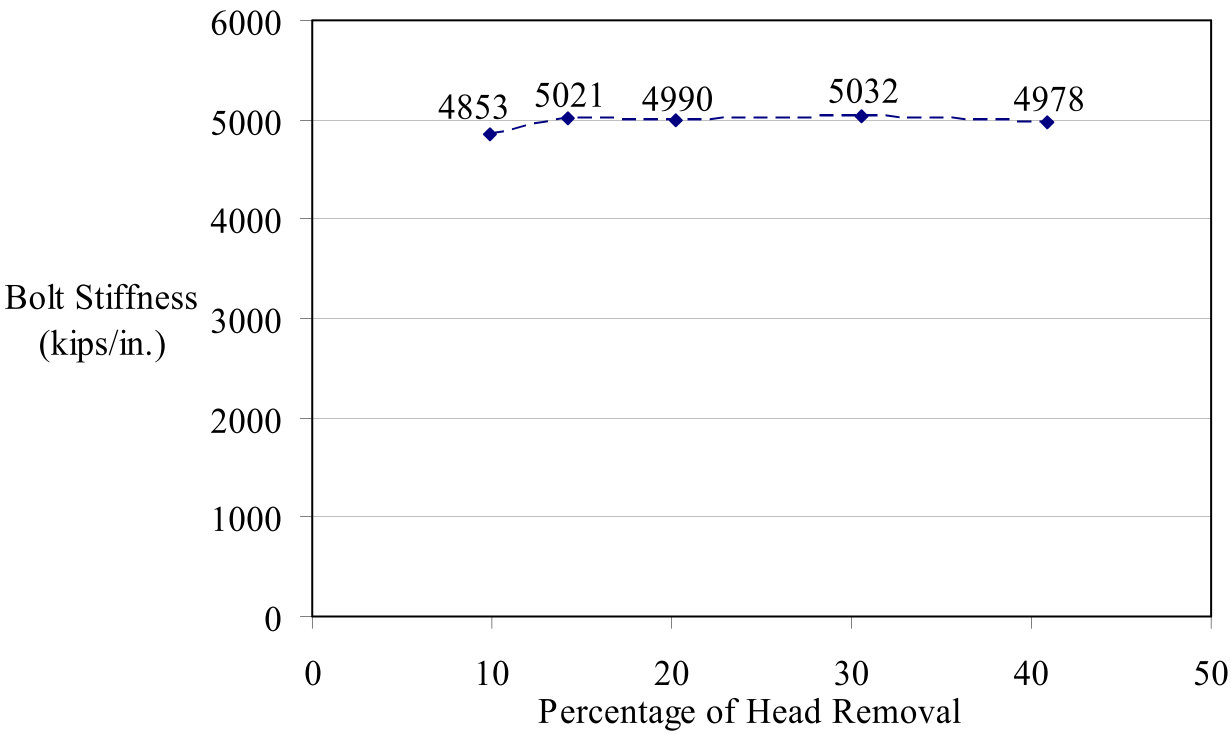


Figure 4.41 Comparison of calibrated stiffness of bolts with various head heights

The calibrated tension results for bolts in each group are shown in Table 4.33.

Table 4.33 Calibrated tension results of bolts with various head heights

Bolt group #	h', head height, after grinding (in.)	(1 - h' / h) x100 head removal percentage	Bolts Tested	K_u^o (kips/in.)	Average ΔL (in.)	Average T_c (kips)	T_c / T_m
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	0.44	10	4	4853	-0.0069	33.5	1.20
2	0.42	14	12	5021	-0.0067	33.6	1.20
3	0.39	20	4	4990	-0.0069	34.3	1.23
4	0.34	31	4	5032	-0.0068	34.1	1.22
5	0.29	41	4	4978	-0.0067	33.4	1.19

Note: h = original bolt head height; h' = bolt head height after grinding; T_c = (ΔL); T_c = calibrated bolt tension; K_u^o = bolt stiffness; ΔL = bolt elongation; T_m = specified minimum pretension (28 kips)

In Table 4.32, bolts in group 2 were manually ground after installation, and bolts in other groups were machine ground before installation. It was found that the bolt stiffness results from bolts in group 2 through 5 were very close, and only the result from bolt group 1 was a little smaller than the other groups. In the bolt stiffness calibration test, bolts in group 1 were loaded up to about 39 kips, while the bolts in other groups were only loaded up to 36 kips. As bolts in group 1 were loaded up to a higher load level than bolts in other groups, part of the threads of bolts in group 1 may have yielded and thus resulted in a lower stiffness value.

It was found from Table 4.33 that the average calibrated tensions of bolts in each group were close. The bolts in group 5 with about 41% head height reduction achieved a lower average pretension than those in other groups.

From the test results shown above, it can be concluded that within a reasonable head height reduction range the amount of material that was removed from the bolt head had no effect on the bolt stiffness, and a limited amount of material removal from the bolt head (less than 31% head height reduction) either before or after the bolt installation had little effect on the achieved bolt pretension.

4.11.4 Examination on Bolt Head Preparation Effect in Skidmore-Wilhelm Calibrator

The preparation effect on the bolt pretension measurement can also be checked directly using the Skidmore-Wilhelm Calibrator. A bolt of the same size and from the same lot as in the previous investigation was installed in the Skidmore and then the bolt head was manually ground to several levels of height to simulate preparation. The change in bolt tension was directly monitored from the Skidmore. Considering the heat caused by the grinding, after each grinding, the reading from Skidmore was not recorded until the bolt was allowed to cool down. Table 4.34 shows the test observation from the Skidmore.

It was found that the bolt experienced a small tension loss in the Skidmore only after considerable amount of head material was removed. Thus, for a limited amount of bolt head material removal there was virtually no effect on the bolt pretension as measured in the Skidmore.

Table 4.34 Grinding effect observation in the Skidmore-Wilhelm calibrator

Grinding Progress (1)	h', head height (after grinding) (in.) (2)	(1 - h' / h) x100 (percentage of head removal) (3)	T_s (4)	T_s /T_m (5)
1	0.42	13	36.0	1.29
2	0.41	15	36.0	1.29
3	0.39	20	35.9	1.28
4	0.36	26	35.6	1.27

Note: h = original bolt head height; h' = bolt head height after grinding; T_s= bolt tension from Skidmore; T_m = specified minimum pretension (28 kips)

4.12 ESTIMATION AND COMPARISON OF THE STIFFNESS OF THE 3-PLATE STEEL JOINT AND THE SKIDMORE CALIBRATOR

As described in Section 4.4.5, the bolt tension results from the pre-installation verification in the Skidmore were higher than the calibrated bolt tension results from the Bolt Gage in the steel joint. It was believed that the difference between the stiffness of the Skidmore and the steel joint was one of the major reasons behind the variation of magnitude in the tension results. Thus the variation in the stiffness of the connected parts is of interest. Tests of bolts in the Skidmore and the solid plate joint were devised to estimate and compare the stiffnesses of the steel joint and the Skidmore calibrator.

A discussion of stiffness is important if there is any interaction between the response of the wrench and the stiffness of the tightened assembly. The relative size, horsepower etc. of the installing wrench were not considered parametrically; one wrench was used throughout the study.

4.12.1 Test Procedure for Stiffness Comparison

Bolts were machine ground on the head and the end to provide two parallel, smooth and flat surfaces before the test. Three Φ 3/4” x 3 1/4” bolts from Manufacturer A were tested to get an average estimation result. The grip length was 2 inches both in the Skidmore and in the 3-plate steel joint.

First, the bolt was placed in the Skidmore. The Bolt Gage was engaged to monitor the elongation of the bolt during the tightening. The dial indicating torque wrench was used to tighten the bolt. The bolt was first snug-tightened to about 8 kips in the Skidmore. Meanwhile, the bolt elongation was recorded using the Bolt Gage, and the corresponding torque was read from the dial. After snug-tightening, match marks were made on the bolt and nut to count the relative turn of nut rotation from snug-tight in the subsequent tightening. Then the bolt was continuously tightened to about 0.0065 in. of bolt elongation as monitored by the Bolt Gage. The elongation of 0.0065 in. was approximately the average bolt elongation value that was achieved in the steel joint installation. After the tightening, the tension result from the Skidmore, torque reading and the turn from snug-tight were recorded.

Secondly, the bolt was tensioned in the 3-plate steel joint following the same procedure as described above. The bolt was first snug-tightened to the same amount of elongation as indicated in Bolt Gage in the Skidmore snug-tightening of about 8 kips in tension. After the match marks were made on the bolt and the nut, the bolt was continuously tightened to about 0.0065 in. of bolt elongation as shown in the Bolt Gage. The relative rotation of nut from the snug-tight fit was recorded. The torque was read from the dial at each step and compared with that from the previous testing in the Skidmore.

4.12.2 Test Observation and Stiffness Comparison

The test observations and the bolt stiffness estimation results are shown in Table 4.35.

From Table 4.35, the average stiffness estimation of the Skidmore and the 3-plate steel joint were 1280 kips/in. and 1910 kips/in., respectively. The stiffness of the 3-plate steel joint was about 1.5 times that of the Skidmore-Wilhelm calibrator.

It was found that when the bolt was tightened in the Skidmore, the calibrated tension from the Bolt Gage was about 2% lower than the Skidmore tension. Immediately after the bolt was tightened, a loss in bolt elongation of about 0.0001 in. was observed from the Bolt Gage, while no change was found on the Skidmore dial.

Table 4.35 Estimation of the stiffness of the Skidmore and the steel joint

Bolt # (1)	Test Progress (2)	*in the Skidmore* Skidmore (kips) (3)	Bolt Gage ΔL (in.) (4)	Bolt Gage T_c (kips) (5)	Turn (^{o}) (from snug) (6)	Torque (lbs*ft) (7)	Stiffness (kips/in.) (8)	*in the steel joint* Turn (^{o}) (from snug) (8)	Torque (lbs*ft) (9)	Stiffness (kips/in.) (10)
1	snug-tighten	8.0	0.0014	7.2	90	90	1300	65	80	1970
	final tighten	33.7	0.0065	32.6		340			320	
2	snug-tighten	8.0	0.0016	7.9	90	80	1270	65	80	1860
	final tighten	33.5	0.0065	32.6		310			300	
3	snug-tighten	7.5	0.0015	7.3	90	90	1280	65	80	1910
	final tighten	33.0	0.0065	32.6		320			300	

Note: T_c = K_u^o (ΔL); T_c = calibrated bolt tension; K_u^o = bolt stiffness from direct tension calibration (5021 kips/ in.); ΔL = bolt elongation

It was also noticed that when the bolt was manually tightened in the Skidmore to an elongation of about 0.0065 in. using the dial indicating torque wrench, the relative rotation of the nut from snug (about 8 kips) was about 1/4 turn. While if TC bolt was installed in Skidmore with the automatic TC wrench, the relative rotation of the nut from snug was about 1/3 turn. In the 3-plate steel joint, the relative rotation of the nut from snug was about 1/6 turn either in the twist-off installation or when the bolt was tightened manually to the average amount of elongation that was achieved during TC bolt installation. Thus when the bolts were stretched to the same amount of elongation both in the Skidmore and in the steel joint, the relative turn of nut from snug was more in the Skidmore than in the steel joint due to the variation of the stiffness of the connected parts. In addition, as compared to the manual torque wrench tensioning, the dynamic motion of the automatic TC wrench made the nut run faster and even further during TC bolt twist-off installation in the Skidmore, and a higher pretension caused by the dynamic effect and interaction with the wrench is a possibility.

The bolt pretensions from the Skidmore pre-installation verification were apparently higher than the calibrated tensions of bolts installed in the steel joints. From the results of the ancillary tests performed here, it can be concluded that this significant variation may have resulted from any combination of several phenomena that are described here:

- As stated in Section 4.4.5, an obvious variation resulted from the difference in the conditions of bolts before tightening. The bolts in the steel joints were tightened right after exposure to the weather in snug-tight condition for certain period of time, while those bolts that were exposed separately were first disassembled and then reassembled for verification in the Skidmore. During the disassembling and reassembling procedure, the bolt thread condition was disturbed, and thus was different from that in the steel joint.

- Since the stiffness of the hydraulic mechanism of the Skidmore is significantly lower than the stiffness of the 3-plate steel joint, more rotation was applied to the nut for the same twist-off bolt to shear off its spine end when it was installed in the Skidmore than in the 3-plate joint, and thus the rate and the total rotation of the special TC wrench experiences are different for the two application. It was noted by Bickford that one problem with the Skidmore calibration is the fact that the torque produced by some tools can be influenced by the stiffness of the joint, and this is especially true for higher speed tools. The dynamic motion of the automatic TC wrench may have thus had some effect on the achieved tension in the Skidmore.

- The bolt tension relaxation effect also had some contributions to the difference. As presented in the Section 4.9, the bolt relaxation occurred mainly in the first few minutes after installation. For the bolts installed in the joint, the stretch data from the Bolt Gage were recorded about half an hour after the bolt installation due to the grounding operation. The tension calibrated from the Bolt Gage was lower than the initial preload in bolt as a result of bolt relaxation effect. While for the tension from Skidmore-Wilhelm Calibrator, no relaxation was observed. As the Skidmore had been used to calibrate the bolt tension for so many times, the surfaces of parts on Skidmore in grip may not contribute to a relaxation effect as the surface of hot rolled structural grade steel might.

- The contact surfaces of the outer plate on the Skidmore calibrator has a potential for changing the frictional component of the torque transferred at the nut face. If the washer were to slip a different portion of the total torque, applied by the wrench, would be applied to the bolt and could result in a different torque to the bolt at the rupture of the splined end.

5. CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the main results, conclusions and observations from this study of the ASTM F1852 twist-off type tension control bolt assemblies. There is a brief summary of the purpose and scope of this research presented as an introduction, followed by the main findings of the report. Numerous ancillary tests to help explain some of the observed phenomena and were reported earlier; not all of these will be discussed further. The summary will deal with the preliminary and ancillary tests separate from those on the main objective regarding delayed exposure. Finally, based on these results, recommendations for potential actions and for further research are presented in the last section.

5.1 SUMMARY

The primary purpose of this research was to study the practical aspects of the installation of black ASTM F1852 twist-off type tension control bolts with particular emphasis on delayed installation. Before various tests were carried out, prototype experiments on smaller samples of bolts were performed to select instrumentation, to design the test specimens, to plan the test procedures and to practice the various steps of the procedures. During this stage, the Bolt Gage technique was perfected and the simulated steel joints were proportioned to be compatible with RCSC Specification's slip specimens. Four manufacturer's products were examined in this study and they have been referred to arbitrarily by a single letter. No attempt has been made to identify the manufacturer and it should be emphasized that the samples of one or two particular lots represent a very small view of their total production. Rather the data should be looked at as a representative sample of what is being produced and used in North America today.

While each fastener assembly is covered by absolute specification requirements on strength, geometry, tolerances and chemical composition, the requirement for lubrication and the specification of the lubrication are stated as a performance criterion that must be verified as part of the production and certification under ASTM1852. This study deals with the use of TC fastener assemblies in construction. This research did not attempt to identify the lubricant nor did it have any knowledge about how the many available products may have been used on the various fasteners tested. The only regard for this important aspect of the fastener assembly property was to report on the observed conditions of the parts of the assemblies as received and to observe them at the various atmospheric exposures and time delays before final installation or pretensioning.

A single manufacturer's product lot was examined first by verifying that the bolts met the ASTM F1852 Specification requirements and the RCSC pre-installation validation. During the bolt tensile strength test, the effect of the number of threads included in the grip of the assembly (the threads included between the contacting nut face and the bolt head) on the bolt tensile strength was studied for the effect on assembly stiffness and the installed tension; stiffness of the assembly is an important parameter in the load determination technique. This test provided information that is generally applicable to all bolts subsequently tested and it was not repeated for other bolt lots or sources.

An initial examination of the lubricant was conducted by attempting to alter or remove the lubricant and to create or simulate a negative lubricant characteristic, e.g. complete absence. Lubricants on ordinary A325 and A490 fasteners are and any "as received" lubrication may not be identifiable or visible. It was observed that the lubricant or the appearance of the surface of the parts varied by manufacturer and two of the lots had a dry finish while another two had bolts with more visible lubricant presence. As part of this study, different solvents/cleaners were applied on the assemblies and installation validation tests were performed to examine variations in the lubricant effect including total removal of the applied lubricant.

The preliminary test parameters investigated in the various experiments were, in summary:

- Geometrical and mechanical properties of the bolts;
- Laboratory calibration of bolt stiffness;
- Effect of bolt head preparation;
- Relaxation and interaction effects in the simulated steel joints;
- Calibration of the Skidmore-Wilhelm tension indicator;
- Installation of bolts with variable thread/washer friction;

In this preliminary phase, the standard verification methods were compared and calibrated. These included the Skidmore-Wilhelm calibrator, small washer type load cells, and the ultrasonic Bolt Gage. Modifications and calibration of the model MS Skidmore-Wilhelm bolt tension calibrator were conducted to provide varying grip lengths for various bolt lengths and to accommodate the torque application using a reaction type electric torque wrench with and without a torque multiplier.

The method of force measurement, the design of the prototype specimens and nature of the critical data were also evaluated. As a result of the preliminary testing, the selected specimen configuration was three steel plates with four bolts and the ultrasonic bolt elongation measurement was chosen for the tension determination. The supplier of the plate specimens asked about slip evaluation of rusted steel, so the specimen was also designed to be suitable for a standard compression type slip test. Slip tests were performed on a limited number of test specimens.

The geometric shapes of the button style bolt heads differed from one manufacturer to another, so the minimum amount of material removed from the head during preparation to achieve suitable coupling of the ultrasound sensor varied. To fit with bolt heads of different shape, two sizes of the Bolt Gage transducers were eventually employed in this project to minimize the material removed during preparation, and the effect of the amount of material removed from the bolt head, (i.e. the grinding/machining effect) was examined in detail. Additional tests such as bolt rotational capacity and interaction effect within a given specimen were done on a limited number of bolts.

The primary test parameters examined in this study were:

- Delayed installation of twist-off type tension control bolt assemblies;
- Effects of temperature and moisture conditions at time of installation on achieved pretension;
- Reinstallation of twist-off type tension control bolt assemblies by the turn-of-nut method.

Bolts from the four manufacturers, three (3) bolts from each lot were measured and tested to verify their qualifications with the various ASTM requirements respectively. The pre-installation verification that is required in the RCSC Specification was also done with the Skidmore-Wilhelm calibrator on a three (3) bolt sample to obtain base line information on properties and performance.

The examination of the effects of delayed installation involved exposure to weather, before final installation; this was the principal field effect that was examined. The time delays were scheduled at 2, 4 and 8 weeks as these periods are considered typical field installation practice. Later it became obvious when exposed specimens were to be "installed" that the conditions of temperature and moisture at the time of the installation also had an effect and lead to further series' where these parameters were examined somewhat more independently.

The investigations on weather/temperature conditions included installation at high temperature (in the summer sunshine), at low temperature (winter), and with wet bolts (joint specimens) to reflect the installation condition during or immediately after rain or melting snow. For each test categories, 12 bolts were installed in the 3-plate joints. To simulate the field conditions, a small snugging preload of about 5~10 kips were applied to the bolts with the operator's full effort on a spud wrench in the 3-plate steel joints before weathering. After the various exposures or weathering, the bolts were installed using the TC wrench; the end surfaces were then prepared for the determination of bolt tension using the Bolt Gage.

Reinstallation of the twist-off fasteners by the turn-of-nut method was performed shortly after the tension release and elongation measurement. Testing of this method for an alternative installation for reuse of the assemblies demonstrated whether or not the changes or conditions associated with the initial installation had any impact on the turn-of-nut installation method and provided basic information for future studies of the changes in the overall response of the assemblies beyond that of the first installation by twist off.

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Based on the results and observations from all of the delayed installation tests, some additional investigations and measurements were performed. These included a comparison of the stiffnesses of the 3-plate steel joint and the Skidmore as well as the use of a strain gaged bolt to check the calibrations of the load measuring instrumentation and provide a better understanding of the fastener's response to the properties of the connections or devices in which it is installed.

From the results of various tests performed in this research, test observations, specific and general conclusions were drawn and are summarized in the following section. Further, some recommendations for continued study and use of the measurement techniques are made according to the test observations and results.

5.2 CONCLUSIONS AND OBSERVATIONS

Based on the test parameters described above the conclusions are separated into two parts. First is a summary of the findings from the preliminary tests; this is followed by the broader conclusions and observations from the main focus of the experimental work. All of the individual results and data were reported in Chapter 4.

5.2.1 Conclusions and Observations from Preliminary Tests

1. According to the ASTM F1852-00 Specification, the TC bolts tested in this program all satisfied the bolt dimensional requirements for ¾ inch diameter bolts of various lengths.
2. The laboratory direct tension test and hardness test were performed according to ASTM F606-00. The test results showed that the TC bolts from each manufacturer were all in accordance with the tensile strength and hardness requirements in ASTM F1852-00 Specification. Specifically, the tensile strength and hardness of bolts from manufacturer B, C and D were quite close to one another, and were higher than those of bolts from manufacture A. For bolts from manufacturer A, the direct tension tests were performed with 3 different grips, 2, 4 and 6 threads exposed between the grips. The measured tensile strength increased as the number of exposed threads within the grip decreased; the ultimate tensile load

increased on average by 1.3 kips as the threads decreased from 6 to 4 in the grip length and by 1.9 kips as the threads decreased from 4 to 2 threads included.

3. Small washer type load cells were evaluated for potential use for pretension load determination by calibrating them. The calibration results showed apparent drifting and hysteretic for the load cells. The lack of satisfaction with the performance of the load cell was the principal reason for discontinuing any further evaluation or use.
4. Among the solvents used to remove the lubricant applied on bolts from manufacturer A, white rice vinegar had the most positive effect on removing that lubricant. Soapy water had some effect, and tri-sodium phosphate (TSP) solution was the least effective. Only the white rice vinegar caused the bolts to not reach the specified minimum tension.

5.2.2 Conclusions and Observations from Primary Tests

1. All of the TC bolts from each manufacturer that were tested in the as-received condition achieved the specified minimum tension as stipulated in the RCSC Specification when installed both in the Skidmore-Wilhelm calibrator and in the simulated steel joints.
2. The average pretension from all twist-off bolts installed in the simulated steel joints was 1.11. This value was significantly lower than the value of 1.27 reported by Kulak and Birkemoe (1993) for fasteners installed in bridges by the turn-of-nut method and not unlike the calibrated wrench average of 1.13 reported in the Guide (Kulak et. al, 1994). The standard deviation for the pretensions from this study was 0.12 compared to 0.25 from the "turn-of-nut" field study. For comparison purposes, Figures 5.1 and 5.2 are presented to show the frequency distributions of the results from these two studies.

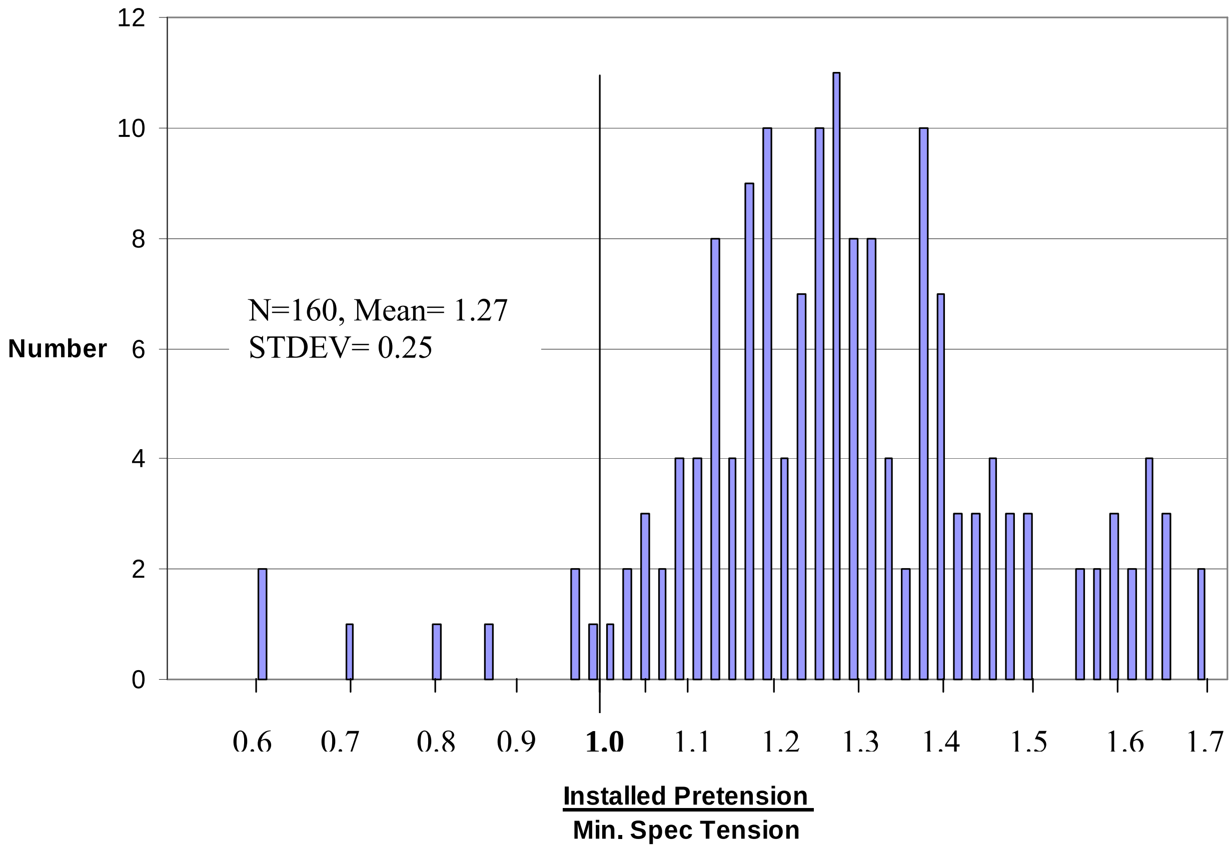

Figure 5.1 Frequency distribution of pretensions from Kulak and Birkemoe (1993) field study of A325 fasteners installed in bridges by the turn-of-nut method

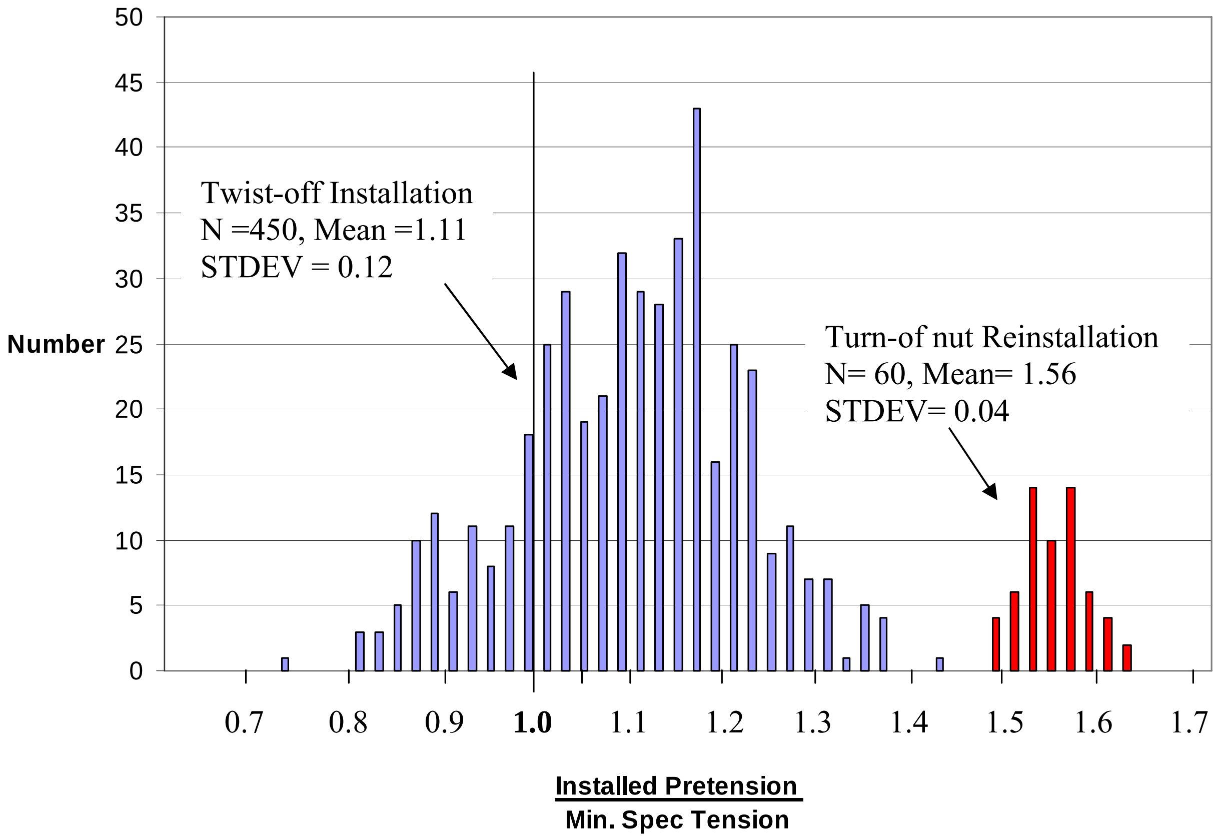

Figure 5.2 Frequency distribution of pretensions of F1852 twist-off bolts installed in simulated steel joints (TORONTO 2005)

3. The TC bolts reinstalled using the turn-of-nut method after twist-off installation are superimposed on the distribution in Figure 5.2. This distribution for a smaller total number of bolts shows the higher installed tension that is achieved by the turn-of-nut method and a smaller standard deviation. This is a rather high mean compared to those reported in the literature for as-received A325 bolts.
4. After the TC bolts were exposed to the weather in the steel joints and in snug-tightened condition for 2, 4 and 8 weeks, the average achieved pretensions in TC bolts tested in this program showed a progressive decline as shown in Figure 5.3. Similarly, the University of Alberta report (1994) showed that the tension-control bolts that were weathered in the joints prior to final installation produced lower pretensions than did the as-delivered bolts. The similar trends in reported in the two studies are illustrated in Figure 5.3.

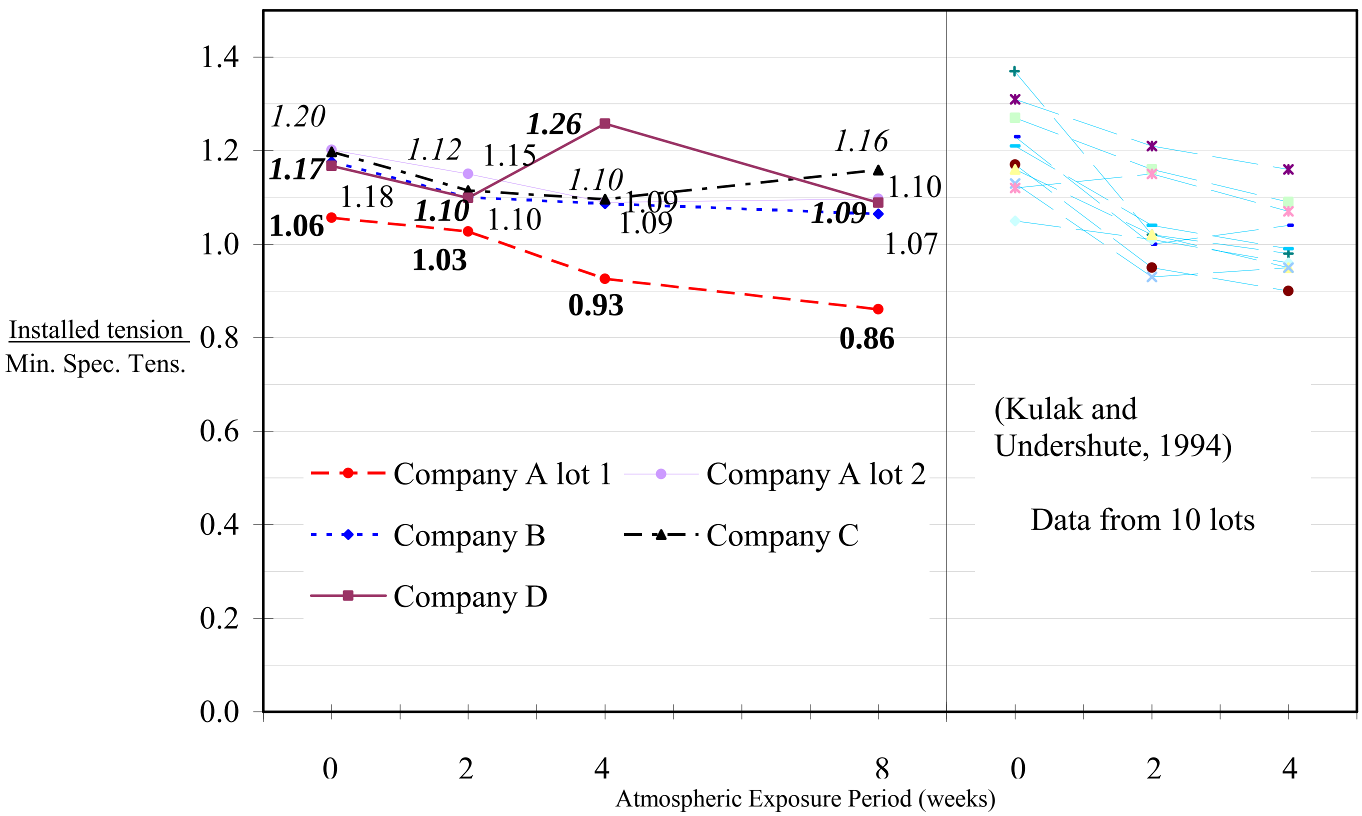

Figure 5.3 Comparison of pretensions from this study with Kulak and Undershute, 1994

5. Generally, TC bolts exposed separately for 2, 4 and 8 weeks passed the verification requirements in the Skidmore when reassembled. In addition, the achieved pretension in the Skidmore was consistently higher than that obtained in the simulated steel joints for the same exposure period. It was also visually observed that loosely weathered assemblies rusted gradually as the exposure period increased. The assemblies went progressively from light rust spotting at 2 weeks of exposure to complete rusting and covered with a thin brown layer at 8 weeks. This was illustrated in figures 4.18 through 4.20. However, no pronounced delayed installation effect was observed in the Skidmore verification. While some variation of achieved tension may be a function of the response of more flexible Skidmore device versus the solid plates, the significant effect is believed to be found in the fact that bolts exposed to weather in loose condition and fasteners snug tightened in steel joints have different behavior. Initially it was thought that the variation in pretension was mainly due to bolt reassembly for the Skidmore installation versus starting from a snug pretension in a

joint. However, bolts that were left disassembled during the exposure period did not have as much thread and lubricant deterioration as did those weathered while snug tightened in the steel joints. As a result, the consistently higher pretensions achieved by bolts installed in the Skidmore are likely caused by the lower stiffness of the tension calibrator, a varying distribution of torsion in the bolt assembly or both.

6. The Skidmore device was more flexible (about 50 percent) than the steel joint and rotation of the TC wrench would tend to run faster and further when the TC bolt was installed in it than it would in the stiffer steel joint. The nature of the Skidmore measurement of bolt tension via hydraulic oil pressure did not permit the sensitivity to determine small losses with time by relaxation; in fact the lower stiffness of the device will result in smaller relaxation of bolt force for the same local changes that cause it in either the steel joint or the hydraulic device.
7. Installed bolts that were removed from the steel and reinserted prior to pretensioning did not show higher pretensions than did the same bolts installed from a snugged condition that had existed throughout the delay. This "reinsertion" variation in installation procedure was attempted only on one lot to investigate a possible method for minimizing the loss of achieved pretension caused by delayed installation. Also, bolts that were loosely placed in the steel joints and not snugged up before being exposed to the environment followed the behavior exhibited by the same assemblies weathered separately. As a consequence, the bolts loosely placed in the steel joints and weathered, achieved higher pretensions than the snug tightened fasteners exposed to weather for the same period. This was anticipated and further supports conclusion number 4 above.
8. Wet bolt installations were performed on as received TC bolts from each manufacturer, because this represented an obvious field parameter that became more apparent after observing some anomalies in the experimental results. Wet bolt installations on both as received and weathered fasteners in the steel joints, showed positive effect on pretensions of bolts from manufacturer C and D, little change on pretensions of bolts from manufacturer B, and some negative effect on bolts from manufacturer A. Thus, <u>moisture present at installation</u> may have <u>a positive or a negative effect</u> on the installed tension in TC bolt assemblies. Specific results were shown in section 4.3. For comparison, Kulak and Undershute (1994) showed that exposing assemblies to humidity for two and four weeks did result in lower pretensions than were obtained for the as-delivered assemblies. In this study the variable

effect of moisture on the achieved pretension appears to be attributable to an interaction of the moisture with the lubricant and/or other surface conditions of contacting parts of the assembly. The effect was apparently removed or diminished when joints were taken inside and allowed to dry overnight before the installation was performed.

9. In two of the tested bolt lots (A and B), the mean value of achieved pretensions in as-received TC bolts was higher at an elevated bolt temperature (~ +41 ^{o}C resulting from direct sunlight in hot summer) and was lower at a degraded bolt temperature (~ -4^{o} C resulting from exposure outside in cold winter) than that achieved at room temperature (~ 24^{o} C). Thus, installation at higher temperature tended to improve installed tension. Also, installation that was attempted under moist and relatively cold conditions (+5^{o} C) and after 8 weeks of exposure, on bolts from manufacturer A resulted in an average pretension 15% lower than the minimum specified.
10. The tensile strengths, hardnesses and average pretensions achieved in as-received bolt assemblies from manufacturer B, C and D were close, and were higher than those of bolts from manufacturer A. In general, higher tensile strength / hardness corresponded to higher installed tensions in ASTM F1852 TC bolts.
11. Reinstallation of TC bolts with the turn-of-nut method achieved higher pretensions than the twist-off installation in all cases, and as expected the average pretension was higher in bolts with higher tensile strength and hardness for turn-of-nut installation method.
12. From the observation of the as-received appearance of the lubrication on TC bolts, the presence of the lubricant on bolts from manufacturer B and D was quite obvious and could be smeared easily, and the presence of lubricant on TC bolts from manufacturers A and C was not visually apparent. For bolts from manufacturers C and D, that had quite similar geometrical and mechanical properties, the average pretension of bolts from manufacturer D that had an obvious heavy lubricant were a little lower than that of bolts from manufacturer C. Thus, bolts with visibly heavier lubrication did not necessarily perform better. Lubrication presence was not always obvious. The quality or nature of the lubricants applied to nuts in TC assemblies appears to be crucial to the achievement of specified installed tensions.
13. The interaction effect between bolts during installation was examined in the 3-plate joint with 4 bolt holes using the Bolt Gage. Little change of bolt pretension was found in the

monitored bolt during the successive tightening of other bolts. Thus the interaction effect did not influence the magnitudes of the tensions reported herein.

14. The amount of material that was removed from the bolt head had no effect on the bolt stiffness, and if a limited amount of material removal from the bolt head (less than 30% head height reduction) either before or after the bolt installation in the steel joints had little effect on the achieved bolt pretension measurements.

5.3 RECOMMENDATIONS

The reduction of the installed tension in ASTM F1852 bolt assemblies brought about by delayed installation was demonstrated and several solution possibilities can be suggested for producing adequate installed tensions. Looking only at the delay effect, the requirement of a higher minimum hardness, higher minimum tensile strength or a higher verification tension (greater than 1.05 x Minimum Specified Tension) would solve the problem in terms of the bolts studied here.

Another important aspect of the results is that the current RCSC requirement for validation by using loose fasteners, that have had equivalent exposure, does not correlate with the performance of snug tight fasteners in the steelwork. A solution to this would be to change the requirement to state that a sample must be removed directly from the steelwork.

Finally, the conditions at the time of installation (moisture, temperature) can have a positive or negative effect that is of the same order as the effect of exposure during delayed installation. Severe cold and/or the presence of moisture at the time of installation were shown to be significant parameters. Using a lubricant, with properties that show the no effect or a positive effect in the presence of moisture is a solution. Similarly, a temperature requirement for a cold performance verification test is a solution and it could be combined with a limit on ambient temperature at the time of installation. Some bolt producers have tested their fastener assemblies for cold weather performance but no such requirement is currently in place in the ASTM F1852.

5.4 RECOMMENDATIONS FOR CONTINUED RESEARCH

Based on the test results and conclusions obtained here, some recommendations on future testing and research are made as follows:

1. From the test results on delayed installation, bolt pretensions appeared to decrease as the time delay increased between initial snug-tightening and final installation. The pre-installation verifications in the Skidmore brought out almost the same results as those of as-received bolts. It indicated that the Skidmore might not be a good indicator of bolt pretensioning after time delay from the snug condition. Further comparisons of tensions achieved in the Skidmore and those achieved in steelwork should be made, particularly for other lengths of bolt where stiffness is theoretically similar.
2. Temperature effects on the installed bolt pretension were only investigated on bolts from manufacturer A and B. To confirm the conclusion that bolt pretension increases as the bolt temperature at time of installation increases, further tests on temperature effect investigation should also be conducted on bolts from other manufacturers. Also, it should be noted that potential problems from high or low temperature effects in the Skidmore or similar devices have not been addressed. The lab tests were all conducted in laboratory environment at room temperature. Furthermore, no investigation of supplementary lubrication techniques was performed in this study. While the RCSC Specification prohibits local application of lubricant, the area of field application of lubricant should be investigated.
3. In general, bolts with higher tensile strength and hardness achieved higher pretensions. In addition, for the direct tension test results, as the grip length, i.e., the number of threads exposed within the grip length is increased, the measured bolt tensile strength decreased. Thus, the grip length might have some effect on the bolt pretension that is achieved in a joint. The test parameter of grip length could be investigated with more tests.
4. When the bolt assembly is installed in the Skidmore, the automatic TC wrench is appears to operate at a higher speed when compared with the steel joint installation. This is thought to be related to the stiffness of the calibrator, and this may in turn interact with the relative size or capacity of the wrench that is used. More observations on the variation of this dynamic

effect of the automatic TC wrench in the Skidmore versus in the steel joint should be carried out to help explain the phenomenon.

5. While rust protection provided by the lubrication of the nut has an effect on the performance after delayed installation, it was observed that the deterioration in achieved pretension by weathered fasteners was probably due to rusting of the bolt. This interaction should be examined; consideration of other applied surface effects or direct rust protection of the bolt should be investigated further.

6. While testing of the slip coefficient was not a formal part of this research, the tests performed here indicated that the specimens used for the delayed installation can be used to obtain valid slip data. And although the results did not represent a large sample, they did agree with the suggested values in the RCSC Specification and they provide additional information on the effect of short term rusting of blast cleaned surfaces. The specimen and procedure used here perform well as a variation on accepted methods of slip load determination.

7. Only black bolts were considered in this study. Twist-off bolts, if galvanized, require an alternative to conventional hot-dip galvanizing such as a mechanically galvanized coating. Earlier studies on galvanized high strength bolts indicate a more stringent lubrication requirement for achieving proper pretension and therefore, a similar study, that includes delayed installation and reinstallation by the turn-of-nut method tests, should be performed on galvanized bolt assemblies.

8. Further study on weathering of bolt assemblies can conveniently incorporate slip testing to increase the data base and to examine other joint faying surfaces slip surfaces that could include roughened hot-dip galvanized or uncoated clean mill scale steel surfaces. The specimens also permit monitoring of elongation loss or relaxation associated with painted and galvanized surfaces on structural steel.

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