Investigation of High-Strength Bolt-Tightening Verification Techniques

BRIDGE ENGINEERING CENTER

Final Report
March 2016

IOWA STATE UNIVERSITY
Institute for Transportation

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About the Bridge Engineering Center

The mission of the Bridge Engineering Center (BEC) at Iowa State University is to conduct research on bridge technologies to help bridge designers/owners design, build, and maintain long-lasting bridges.

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16. Abstract

The current means and methods of verifying that high-strength bolts have been properly tightened are very laborious and time consuming. In some cases, the techniques require special equipment and, in other cases, the verification itself may be somewhat subjective. While some commercially available verification techniques do exist, these options still have some limitations and might be considered costly options.

The main objectives of this project were to explore high-strength bolt-tightening and verification techniques and to investigate the feasibility of developing and implementing new alternatives. A literature search and a survey of state departments of transportation (DOTs) were conducted to collect information on various bolt-tightening techniques such that an understanding of available and under-development techniques could be obtained. During the literature review, the requirements for materials, inspection, and installation methods outlined in the Research Council on Structural Connections specification were also reviewed and summarized. To guide the search for finding new alternatives and technology development, a working group meeting was held at the Iowa State University Institute for Transportation October 12, 2015. During the meeting, topics central to the research were discussed with Iowa DOT engineers and other professionals who have relevant experiences.

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INVESTIGATION OF HIGH-STRENGTH BOLT-TIGHTENING VERIFICATION TECHNIQUES

Final Report
March 2016

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EXECUTIVE SUMMARY

The ability of a connection to transfer loads through the components relies heavily on whether the connection is properly installed. In a bolted connection, it is important to obtain an adequate initial clamping force and to ensure that the initial clamping force does not dissipate over time. Therefore, proper inspection of the connection and verification of the likely clamping force are needed to help ensure that such connections are capable of performing their functions safely.

The current means and methods of verifying that high-strength bolts have been properly tightened are very laborious and time consuming. In some cases, the techniques require special equipment and, in other cases, the verification itself may be somewhat subjective. While some commercially available verification techniques do exist, there are drawbacks such as being costly, time-consuming, and impractical to use in the field.

The primary objective of this project was to explore the current state-of-practice and the state-of-the-art techniques for high-strength bolt tightening and verification in structural steel connections. This research was completed such that insight could be gained on available technologies that could lead to investigating the feasibility of developing and/or implementing new alternatives.

A literature review was conducted to obtain information on a variety of related topics including available bolt-tightening and verification techniques. An online survey was created and disseminated across the nation to identify technologies currently in use by other states and to help guide the research and discover new techniques. The topic of bolt tightening was discussed with Iowa Department of Transportation (DOT) engineers and other professionals who have relevant experience during a working group meeting held October 12, 2015 to guide the search for new alternatives and technology development.

1. INTRODUCTION

1.1. Background

For many years, bolts have by far been the most common type of fastener used for assembling structural connections. Due to their ease of installation and economy, bolted connections are frequently utilized in civil applications as well as in industries such as automotive, petroleum, and aeronautics. The main function of bolted connections is to join structural members to safely transmit loads from one component to the other. As such, bolted connections are critical components of any steel structure.

The idea behind a bolted connection is that, as steel components are tightened, a bolt (or a group of bolts) acts as a spring and pulls the components together. The reliability of bolted connections is largely controlled by the level of initial clamping force and by the stability of the clamping force over time. One common misconception is that correct tightness is dependent upon the torque applied to a bolt or a nut. The true strength of a bolted connection comes from the tension (or clamping force) developed in the bolts through tightening. Although many tools utilize torque to twist a bolt head (or nut) to effectively stretch the bolt, it is not accurate to say that a specific amount of torque will always yield a specific amount of tension in the bolt.

For many types of structural systems, a failure of a bolted connection is often due to an improper installation, which may lead to collapse or extensive system-wide damage. While failure of a single non-critical fastener may not be significant to structural stability and serviceability, an inadequate installation of bolts in a connection may result in excessive vibration or insufficient stiffness of a member. For example, if a connection is not adequately tightened, it may become loose and allow the components to separate; if over tightened, on the other hand, it may alter the mechanical properties of the bolt and result in damaging the connection. In general, the ability of a connection to transfer loads through the components relies heavily on whether the connection is properly installed. Therefore, adequate bolt-tightening verification is needed to ensure that such connections are capable of performing their functions safely.

The current means and methods of verifying that high-strength bolts have been properly tightened are both very laborious and time consuming. In some cases, the techniques require special equipment and, in other cases, the verification itself may be somewhat subjective. While some commercially available verification techniques do exist, there are drawbacks such as being costly, time-consuming, and impractical to use in the field.

1.2. Objectives and Scope

The primary objective of this project was to explore the current state-of-practice and the state-of-the-art techniques for high-strength bolt tightening and verification in structural steel connections. This project was completed so that insight could be gained on available technologies that could lead to investigating the feasibility of developing and implementing new alternatives.

The research effort involved the following four tasks:

Task 1 – Literature Review

A literature review was conducted to obtain information on a variety of related topics. For example, literature on conventional bolt-tightening techniques was collected, reviewed, and summarized. Because it is known that there are some bolt-tightening verification techniques used by other industries, this effort was extended to fields outside of structural engineering so that an understanding of available and under-development techniques could be obtained.

Task 2 – Survey of States

A set of online questions was created and disseminated via the Iowa Department of Transportation (DOT) bridge engineer to his colleagues across the nation. The goals of this survey were to identify technologies currently in use by other states and to help guide the research and discover new techniques. The survey asked general questions about bolt tightening, common practices used, and whether respondents were considering any new alternatives or aware of any relevant technologies under development.

Task 3 – Working Group Meeting

A number of people/organizations within Iowa State University (the Institute for Transportation, the Ames Laboratory, the Center for Nondestructive Evaluation, etc.), the Iowa DOT, the Iowa consulting engineering community, and the Iowa contractor community may have knowledge related to improving the state-of-the-practice with respect to bolt-tightening verification. To facilitate discussion among these resources and other interested parties, a working group meeting was held at the Institute for Transportation October 12, 2015. The main goals of the meeting were to identity existing bolt-tightening verification technologies including those not readily utilized and to brainstorm new means and methods (e.g., instruments with innovative metallurgical properties) that may provide viable options if additional research were to be conducted.

Task 4 – Final Report

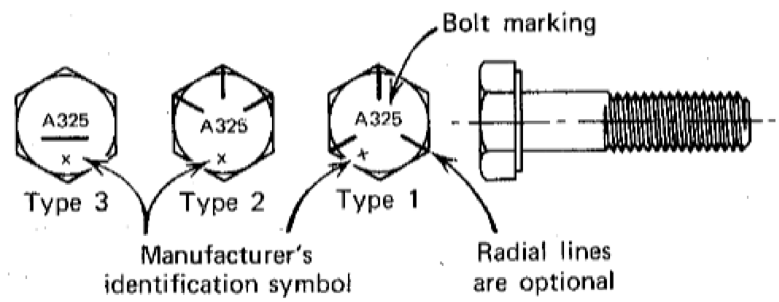
All of the work completed during this project was summarized in this final report that consists of four chapters. Chapter 1 presents the project background and objectives. The literature review summaries on bolted connections, bolt tightening, and verification techniques are presented in Chapter 2. The results and discussion of the survey and the working group meeting are summarized in Chapter 3, while general concluding remarks and recommendations are given in Chapter 4.

2. LITERATURE REVIEW

2.1. Structural Steel Bolts

Bolts are one of the primary mechanical fasteners used to connect structural steel and to transfer loads between components. Although a variety of bolts are used in construction, the three most common structural bolts include ASTM A307, ASTM A325, and ASTM A490 bolts. Of these three, A307 bolts are considered low-strength while A325 and A490 bolts are specified as high-strength bolts. A307 bolts have an ultimate tensile strength of about 45 to 60 ksi, distinguishing them from the high-strength bolts that have an ultimate tensile strength at least twice as great. Although A307 bolts may offer economical solutions for many applications, their usage is generally limited to temporary or lightly loaded structures (Kulak et al. 2001).

A325 bolts are made of heat-treated, tempered, medium carbon steel. There are three different types of A325 bolts: Type 1 is made of medium carbon steel, Type 2 is made from low-carbon martensite steel, and Type 3 is made from atmospheric corrosion-resistant steel. Each type is distinguished by a different bolt head marking as shown in Figure 2-1 (Kulak et al. 2001).



Kulak et al. 2001 Copyright 2001 Research Council on Structural Connections

Figure 2-1. Bolt head marking for A325 bolts

Most specifications require that both the heads of the bolts and the nuts be marked so that they can be easily identified.

A490 bolts are made in a similar fashion to A325 bolts but with an alloy steel. There are three different types of A490 bolts: Type 1 bolts are made of alloy steel, Type 2 are made of low-carbon martensite steel, and Type 3 are made of atmospheric corrosion-resistant steel. The bolt heads are marked in a similar fashion to the A325 bolts shown in Figure 2-1, except with an A490 marking (Kulak et al. 2001).

Although both A325 and A490 bolts are high-strength bolts, A490 bolts display greater mechanical properties and are less ductile and more expensive compared to A325 bolts. Another important difference between the two is that while A325 bolts can be galvanized if necessary, A490 bolts should not be galvanized due to the risk of stress corrosion cracking and hydrogen embrittlement (Kulak et al. 2001). Thus, the use of A490 bolts for bridges or other highway structures is very limited if not prohibited.

2.2. Bolted Connections

Bolted connections can be subjected to different types of forces including flexure, shear, axial, torsion, or any combination of these. In most cases, however, connections are configured so that bolts resist shear and axial loads regardless of how they are loaded. One of the first steps in the process of constructing a bolted connection is to determine what type of connection it is. By determining the joint type, proper bolt selection and installation can be followed. The three most conventional joint types in structural steel are snug-tightened, pretensioned, and slip-critical joints. The designation of each type is dependent on how a connection is to be used to transfer loads throughout a structure. Table 2-1 summarizes classifications of these joint types.

Table 2-1. Summary of applications and respective joint designations

Load Transfer	Application	Joint Type
Shear Only	Resistance to shear load by shear/bearing.	Snug-tightened
	Resistance to shear by shear/bearing. Bolt pretension is required, but for reasons other than slip resistance.	Pretensioned
	Shear-load resistance by friction on faying surfaces is required.	Slip-critical
Combined Shear and Tension	Resistance to shear load by shear/bearing. Tension load is static only.	Snug-tightened
	Resistance to shear by shear/bearing. Bolt pretension is required, but for reasons other than slip resistance.	Pretensioned
	Shear-load resistance by friction on faying surfaces is required.	Slip-critical
Tension Only	Static loading only.	Snug-tightened
	All other conditions of tension-only loading.	Pretensioned

Source: Research Council on Structural Connections (RCSC) 2009

Snug-tightened joints do not require preinstallation verification as there are no requirements related to torque, pretension, or number of turns. (Criste 2012)All pretensioned joints begin with a snug-tight condition and progress to a defined level by the induced pretension. The basic principles of the pretensioning methods used for pretensioned and slip-critical joints are essentially the same. Although some slip resistance will be present in all connections regardless of the joint type, not all connections are required to be slip-critical. The main difference between pretensioned and slip-critical joints would be the faying surfaces that need to be prepared for slip-critical joints to meet a specified level of slip resistance. Slip-critical joints transfer service shear-load through the frictional resistance of the bolted plies. The magnitude of slip resistance depends on the pretension present and the roughness of the faying surfaces (Criste 2012). The Research Council on Structural Connections (RCSC) prepares specifications and documents related to structural connections. Sections 4.2 and 4.3 in their *Specification for Structural Joints Using High-Strength Bolts* (or the American Institute of Steel Construction (AISC) Specification J1.10 and J3.2) discuss when a connection is classified as pretensioned or slip critical, respectively (RCSC 2009, AISC 2011).

Once the joint type is distinguished and proper bolts are selected, a connection can be installed in accordance with ASTM and the RCSC specifications. The success of a bolted connection depends largely on adequate tightening of bolts. Since bolts behave somewhat like springs, proper utilization of the bolt's elastic properties can lead to correct tightening. In operation, an axial pre-load tension is exerted on each bolt during the tightening process. This axial pre-load tension is referred to as the "tightening load" or "pretension" and is typically almost equal in magnitude and opposite in direction to the compression force applied on the assembled components. Failure to achieve the necessary pretension may lead to serious and undesired structural behavior such as an increased displacement in a joint that may cause additional second-order bending effects or lead to a fatigue-type failure. The purpose of pretensioning depends on the needs of an application that may include the following:

- Ensure proper rigidity of an assembly in supporting external loads
- Prevent leakage at seals
- Avoid shear stresses on bolts
- Resist spontaneous loosening effects
- Reduce dynamic load effects on the fatigue life of bolts (Dalal and Thakur 2013)

Bolts can be tightened to a desired initial pretension so that the connected parts are tightly held together between the bolts and the nut heads without allowing slip at the interface. Steel washers can be used in a connection to evenly distribute the clamping force on the bolted surfaces and to prevent the threaded portion of the bolt from bearing on the connecting components. The surfaces in contact need to be free of mill scale, rust, paint, grease, and other obstructions.

The RSCS specifies that the minimum pretension be set at 70% of the specified tensile strength of a fastener (e.g., ASTM A325 and A490). The minimum bolt pretension for pretensioned and slip-critical joints can be found in Table 8.1 of the RSCS specification (RCSC 2009) or Table J3.1 of the AISC specification (AISC 2011). Neither the AISC nor the RCSC recommends the use of prescribed torque values as a valid means of applying necessary pretension (Criste 2012). This is due to the fact that the friction coefficient within the assembly may be significantly different from project to project (and even among the fasteners used within a project) and that the variation of the torque corresponding to a pretension largely depends on thread fit, nut surface condition, grip surface condition adjacent to the nut, and other factors (Criste 2012). One exception to this would be the use of the calibrated wrench method, which will be further described later in this report. Although the calibrated wrench method is a torque-based method, it is recognized by the RSCS as a suitable method for high-strength bolt tightening because the required torque is established by measuring the installed pretension and preinstallation verification is conducted prior to the real installation. The specification requires that the calibration be performed daily or any time conditions change.

2.3. Bolt-Tightening Methods

A typical bolt assembly consists of an externally threaded screw (known as a bolt) and a nut. If a washer is used, it becomes an essential part of the assembly as well. Each component should be in compliance with the appropriate ASTM International specifications to ensure the strength and quality of each part. Obtaining the desired bolt pretension is always the objective at initial assembly of each connection. One of the common issues in a bolted connection is insufficient pretension, which can be caused by selecting an inappropriate tightening method. It is important for engineers to understand the features and characteristics of the method used since the precision and accuracy of pretightening may depend on the method selected. A brief description of various bolt-tightening techniques is presented in the following sections.

2.3.1. Torque Control Method

Torque control tightening is one of the most widely used methods for bolted joint assembly and is known to be effective particularly at lower levels of pretension. With this method, a bolt is tightened within the elasticity limit, i.e., the elongation and the axial tension of the bolt are proportionate, and the bolt-tightening process stops when a selected peak torque has been reached. The nominal torque necessary for bolt tightening can be determined from existing torque specification tables (commonly known as bolt torque tables) or by directly studying the relationship between the applied torque and the resulting bolt tension. During tightening, the shank of the bolt sustains torsional stress and elongation. Most torque specification tables ignore the torsional stress and assume a direct stress in the threads of, in most cases, 70 to 75% of the bolt yield stress (Bolt Science Limited 2015).

Although torque control and operation may be relatively easier than other methods, a fundamental disadvantage associated with the torque control method is that the torque-pretension relationship is highly sensitive to the friction properties of an assembly (e.g., underhead bearing friction, thread friction). It is estimated that approximately 90% of the input torque is consumed to overcome the underhead bearing and thread friction during tightening of the threaded fasteners (Meng 2008). Even small variations in the friction conditions may lead to significant differences in bolt pretension (up to approximately ±50%) (Göran 2003). This variation may be too large to use this method in critical applications. This effect, however, can be minimized by the use of frictional stabilizers that can be coated onto the fasteners to reduce the frictional variations. Other factors that affect the torque-pretension relationship include the material used, joint and fastener geometry, surface finishes, type of thread, heat treatment, lubrications and plating, and sometimes the tightening speed (Meng 2008).

2.3.2. Angle Control Method

Angle control tightening is a method in which a bolt is tightened to a prescribed rotation beyond an initial condition. In general, two steps are involved. First, the bolt is tightened with a conventional wrench until it reaches approximately 70 to 75% of the bolt's ultimate strength (Bickford 2007). After the first tightening, the prescribed rotation is added. This additional turn elongates the bolt, thereby developing the bolt tension. A desired pretension is achieved by tightening the bolt past the yield point. Tightening over the yield point results in the pretension being less affected by friction than in the case of elastic tightening (i.e., torque control tightening). The yield characteristics of a fastener determine the pretension and its variation, which is often less than ±10% (Zhang et al. 2012). However, this method requires a precise determination of the angle to be rotated as there is a possibility of over tightening due to the fact that the rotation angle in the elastic region is usually small.

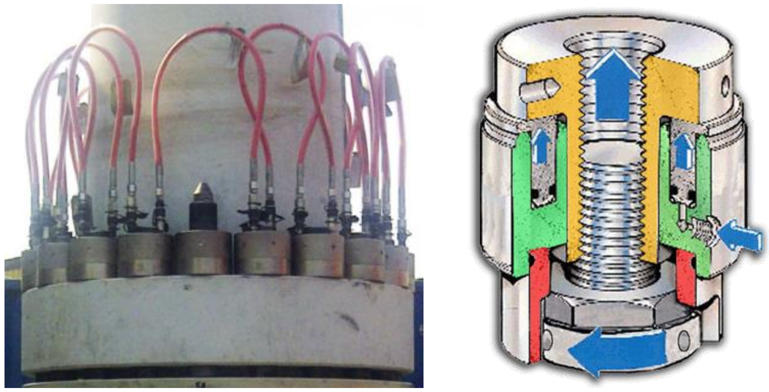
2.3.3. Yield Control Method

Also known as joint control tightening, the concept of bolt tightening to yield was first introduced by the Association of American Railroads (AAR) about 50 years ago (Meng 2008). This method requires measurement of the torque and the rotation applied during tightening. It relies on the material properties to stop the tightening process regardless of the magnitude of the applied torque. A typical tightening system consists of two components: a tool capable of measuring torque and angle and a controller with yield-computing capabilities. The system monitors the elastic slope of the torque-angle signature of the joint past the initial threshold torque, and stops the tightening process when a change in slope is detected and that signifies the beginning of material yielding. Since the tightening to yield produces small variance in bolt tension compared to the torque control or angle control methods, it allows for achieving accurate clamping forces and minimum bolt elongation past yield without the need for calibration. Although the yield control tightening method has been frequently adopted in mass production applications such as an automotive assembly plant, its use is limited to ductile bolts that have a "long" plastic elongation region. Tightening bolt to yield on brittle bolts should be avoided (Meng 2008).

2.3.4. Elongation (or Stretch) Control Method

The basic principle of the elongation (or stretch) control method is that the tension developed within a bolt is directly related to its elongation (Bickford 2007). When applying torque to a bolted connection, a bolt is being stretched until a necessary clamping force, or pretension, is developed. The necessary pretension in the bolt can be obtained by controlling the load applied to the bolt being tightened. To avoid certain errors related to friction, some industries utilize methods in which a bolt is elongated without applying torque. The primary factors that affect the relationship between the bolt elongation and the bolt tension are those related to the axial stiffness of the bolt (Meng 2008), which can be determined by conducting a simple tensile test to measure load-elongation of the bolt. A small amount of reduction in pretension is expected as the nut would also elastically deform under the applied load. The accuracy and reliability of the bolt elongation method for bolt tightening requires the change in length of the bolt to be measured with high precision (Meng 2008). This can be done with the use of a bolt elongation measuring device such as a micrometer, a gage screw, gage rod bolts, or an ultrasonic device.

The use of a hydraulic tensioning device is quite common for the elongation control method (similar to post-tensioning of steel cable). Hydraulic tensioning (Figure 2-2) is a technique that directly elongates a bolt to develop a necessary pretension in a connection (SCHAAF GmbH & Co. KG 2015).



Haitor 2015 (left) and Hevii Technologie 2016 (right)

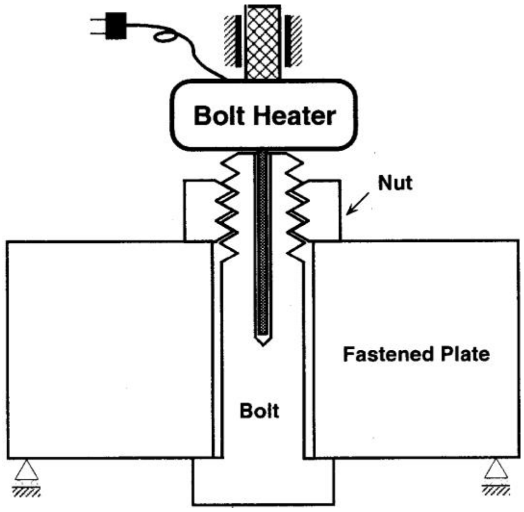
Figure 2-2. Hydraulic tensioning devices

In this method, a bolted connection is first assembled such that the bolt end is protruding past the nut. Then, a hydraulic tensioner is placed over the connection so that it can grasp the bolt end. Once pressure hoses are connected, a predetermined pressure is applied by a jack and the bolt is stretched without turning the nut. Because the force is applied directly to the bolt end, the tension equal to the force generated by the jack is developed in the shank of the bolt. After the required pretension is developed, the pressure is maintained while the nut is tightened. Once the nut is properly tightened, the pressure is released and the bolt is kept in its tensioned state, providing the necessary clamping force to the connection. Oftentimes, this method is used when large diameter bolts are used in a connection. Some advantages of hydraulic tensioning include the following (SCHAAF GmbH & Co. KG2015):

- No torsional stress produced in the bolt because it is directly elongated
- Better accuracy of bolt pretension than torque-based methods
- Small variance of friction between bolted components
- Reduced risk of damage to components from over-torqueing to overcome friction
- Relatively easy installation without needing to exert much physical effort

2.3.5. Heat Control Method

The heat control tightening method utilizes the thermal expansion characteristics of the bolt being tightened. This method is often used for critical structures with large diameter bolts (≥4 in. or 100 mm in diameter) that are difficult to be clamped by other means (Fukuoka and Xu 2002). A typical bolt used in this application has a predrilled hole in which a bolt heater can be inserted down the axis of the bolt so that heat can be applied to cause elongation of the bolt (Figure 2-3).



Fukuoka and Xu 2002 © 2002 American Society of Mechanical Engineers (ASME)

Figure 2-3. Fastened connection utilizing a bolt heater

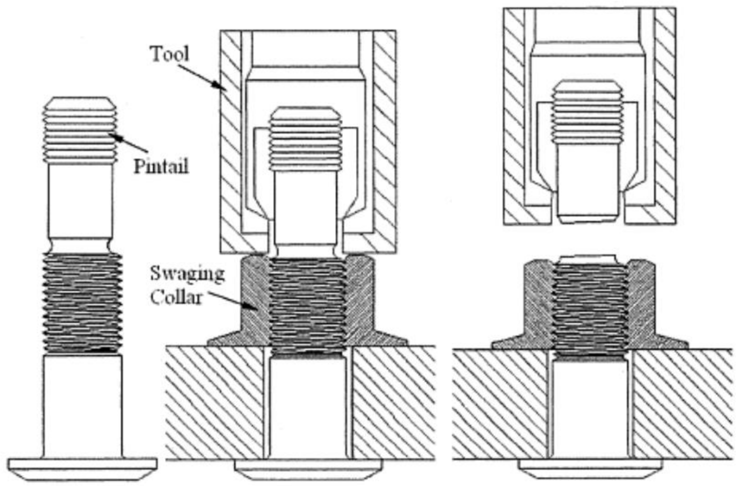
Methods of heating include sheathed heating coil, carbon resistance elements, and direct flame. Once the predetermined elongation is reached, the nut is run down onto the surface of the fastened joint by using the turn-of-nut method, which is described subsequently. The tension in the bolt is generated as the bolt cools and attempts to return to its original length. The tightened nut resists the change in length of the bolt.

In comparison to other methods that are used for large diameter bolts, the heat control method can be useful especially when tightening is needed in narrow working conditions (i.e., not enough clearance). In addition, the method does not cause torsional stresses in the bolt. However, this method is not widely used due to some notable disadvantages: bolt tightening with a bolt heater is a slow process, the clamping force can only be verified after the connection has completely cooled, high temperature may alter the mechanical properties of the components in the connection, and it requires skilled workers (Fukuoka and Xu 2002). The use of this method may not be proper for tightening short bolts due to a risk of high error.

2.3.6. Tension-Indicating Method

The tension-indicating method includes the use of special devices to indirectly measure the pretension. The most commonly used tension-indicating device in civil engineering applications is a direct-tension indicator (DTI) washer. Such a washer has small, raised, hollow bumps on one side that are intended to plastically deform under an applied clamping load. The desired pretension is obtained when a predetermined gap is present between the washer and the underhead of the bolt. The gap is measured using a feeler gage. Some newer types of washers (e.g., Squirter DTI washer) utilize hollow bumps filled with colored silicone, which squirts out once the bumps are compressed. More information on tension-indicating washers is given subsequently.

Another example of tensioning indicating devices is a lockbolt (Figure 2-4).

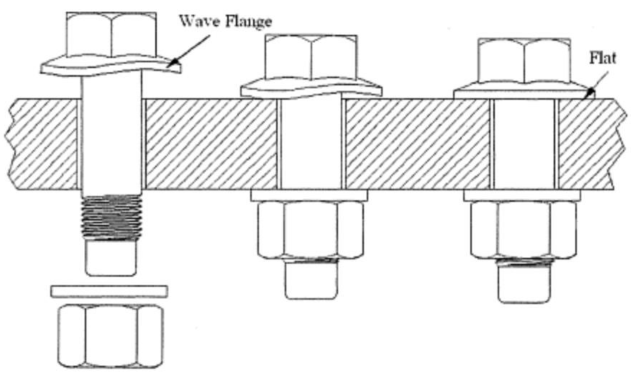


Meng 2008

Figure 2-4. Lockbolt

The necessary tension is applied with the use of a tool that pulls the pintail until it breaks free while the collar is swaged onto the end of the fastener to retain the tension. The major difference between the lockbolt and a twist-off-type bolt is that the tightening of the lockbolt is controlled by tension, not by torque (Meng 2008).

Figure 2-5 shows a different type of a tension-indicating bolt known as a DTI bolt (Bickford 2007).



Meng 2008

Figure 2-5. Tension-indicating bolt with wave flange

A DTI bolt assembly consists of a bolt, a nut, and a wave washer that does not have protrusions. In a typical application, the nut is tightened until the wave flange is flattened. One advantage of the DTI bolt is that the deformation of the flange is elastic (i.e., the “waves” of the flange will rise up to indicate the tension loss in the bolt) (Meng 2008).

Some tension-indicating bolts utilize a built-in visual indicator. One such tension-indicating bolt (Figure 2-6) is called a SmartBolt (Stress Indicators, Inc. 2015).

Meng 2008 (left) and Stress Indicators, Inc. 2015 (right)

Figure 2-6. Tension-indicating bolt with indicator fluid

As the bolt is tightened, the bolt is elongated and the gauge pin moves away from the window allowing the indicator fluid interposed into the gap between the disk and the transparent window in the head of the bolt, triggering a color change that can be observed through the transparent window. Although the color change is gradual, it mostly takes place in the final 10 to 15% of the tightening sequence, providing sensitivity and tension resolution (Bickford 2007).

2.4.Current State-of-the Practice in the US

Five techniques are currently recognized by the RSCS as suitable for installing high-strength bolts in the US (RCSC 2009):

- Snug-tightened
- Turn-of-nut pretensioning
- Calibrated wrench pretensioning
- Twist-off-type tension-control bolt pretensioning
- Direct-tension-indicator (DTI) pretensioning

The snug-tightened method can only be used for snug-tightened joints while the other four methods are used for joints specified as pretensioned or slip-critical joints. Each of these methods can be used independently of the others. The installation requirements can be found in Section 8 of the RCSC specification (RCSC 2009).

It is important to note that adequate bolt tightening requires proper handling and storage of all components, as well as following appropriate tightening procedures regardless of the method being used. Chapter N of the AISC specification provides the inspection tasks that need to be conducted before, during, and after bolt tightening (AISC 2011). Also, the criteria for proper inspection of bolted joints can be found in Section 9 of the RCSC specification (RCSC 2009).

2.4.1. Snug-Tightened

Snug-tight is commonly known as “ordinary effort of worker using a spud wrench” or “the first impact of an impact wrench” or 20 percent of the “tension” value listed in Iowa DOT Standard Specifications for Steel Structures Article 2408.03, S, 5, a, 6 and having all faying surfaces in tight contact. According to the RCSC, the snug-tightened condition of a bolted connection is defined as “the condition that exists when all of the plies in a connection have been pulled into firm contact by the bolts in the joint and all of the bolts in the joint have been tightened sufficiently to prevent the removal of the nuts without the use of a wrench” (RCSC 2009). The high-strength bolt manufacturer is required to test combinations of bolt, washer, and nut to establish a rotational capacity lot number and containerize all tested bolts, washers, and nuts with the rotational capacity lot number to help ensure that the same combination of tested elements are used together during field installation.

Snug-tightened joints are frequently found in shear- or tension-type connections where pretension is not needed. In some structures, specific joints are designed to allow a certain rotation to reduce the moment transferred to a connection. Snug-tightened joints are typically used where slip of a connection is not considered to be a failure of the connection. These types of joints normally utilize the increased shear strength of high-strength bolts (RCSC 2009).

Given that a specified pretension is not required for snug-tightened joints, their inspection process is quite simple. Once an inspector ensures that proper components have been used, all that is needed is verification that the plies of connected elements are in firm contact and that the bolts are tightened so that the nuts cannot be turned without the use of a wrench. During the process of snug tightening the fasteners in the splice, the snug tightening must progress from the center of the splice to the outside of the splice, in the horizontal and vertical direction, and then be rechecked back to the center to ensure that the plate plies are in full contact and that the fasteners have not loosened. If insufficient tightening is suspected in a connection, it needs to be verified by physically checking the connection (RCSC 2009). After all fasteners in a splice have been tensioned, the inspector is required to monitor check at least 10% of the fasteners (minimum of two fasteners) in the splice using the calibrated torque wrench. If any bolt or nut is turned at torque values below the inspection torque value(s), the inspector needs to check all fasteners in that connection, and tighten and re-inspect all bolts or nuts.

2.4.2. Turn-of-Nut Pretensioning

Turn-of-nut pretensioning (Figure 2-7) is based on the application of a specific minimum elongation as a means of controlling high-strength bolt pretension.

Mark bolt, nut, and steel plate   Desired position achieved (1/3 turn illustrated)

Figure 2-7. Turn-of-nut pretensioning

A typical installation starts by tightening the fastener to a snug-tight condition to bring the connected parts into solid contact. The snug-tight condition is necessary to compensate for start-up variables such as a slip of the bolt head, a bent washer, and/or out-of-flatness of the joint members that would require more than the specified turns to reach the required minimum (Tan et al. 2005). Applying the specified turn (or turns) to stretch the bolt to a specific amount (beyond the torqued-tension proportional limit of the bolt) provides the final control of the elongation necessary to develop the required pretension. The actual pretension depends on how far the nut is turned as well as how much clamping force was established prior to the turning. The required rotation angle is determined based on the fastener's length and diameter, and the slope of the plies as summarized in Table 2-2.

Table 2-2. Nut rotation from snug-tight condition for turn-of-nut pretensioning[a, b]

	Disposition of Outer Faces of Bolted Parts		
Bolt Length[c]	**Both faces normal to bolt axis**	**One face normal to bolt axis, other sloped not more than 1:20[d]**	**Both faces sloped not more than 1:20 from normal to bolt axis[d]**
Not more than $4d_b$	1/3 turn	1/2 turn	2/3 turn
More than $4d_b$ but not more than $8d_b$	1/2 turn	2/3 turn	5/6 turn
More than $8d_b$ but not more than $12d_b$	2/3 turn	5/6 turn	1 turn

a Nut rotation is relative to bolt regardless of the element (nut or bolt) being turned. For required nut rotations of 1/2 turn or less, the tolerance is plus or minus 30 degrees; for required nut rotations of 2/3 turn and more, the tolerance is plus or minus 45 degrees.

b Applicable only to joints in which all material within the grip is steel.

c When the bolt length exceeds 12db, the required nut rotation shall be determined by actual testing in a suitable tension calibrator that simulates the conditions of solidly fitting steel.

d Beveled washer not used.

Source: Research Council on Structural Connections (RCSC) 2009

In order to minimize the relaxation of the tightened bolt, both the snug-tightening and the subsequent additional turning process must proceed systematically from the most rigid part of the joint to the least rigid part (Tan et al. 2005).

Before pretensioning is applied, it is recommended that bolts, nuts, and steel surfaces of a connection be match-marked in the snug-tight condition. Although match marking is not a requirement, it allows for an easy visual inspection after final tightening. If match marking is not used, careful inspection during the installation is required to assure that the proper methods are followed. An example of the recommended marking procedure for a one-third turn is depicted in Figure 2-7. It is important to note that proper installation depends on joint compactness and securely holding the bolt head while the nut is turned.

The following steps summarize the turn-of-nut pretensioning procedure:

1. Bring the assembly into firm contact and apply full effort with a spud wrench or apply a few impacts with an impact wrench until a solid sound is heard (i.e., snug-tightened condition)
2. Once a snug-tight condition is verified, match-mark the bearing face of the nut, the steel plate (to ensure that the bolt does not rotate in the splice), and the end of the bolt with a single straight line
3. Apply the prescribed turn (Table 2-2) using a systematic approach that would involve an appropriate bolting tightening pattern

The turn-of-nut pretensioning method often yields more accurate results than torque-controlled pretensioning methods. This is due to the fact that, if installed correctly, match-marking allows for uniform bolt pretensioning and because strain-control is known to be more reliable than torque-control in the inelastic region of bolts. Also, the uncertainty due to friction within the components of a connection is much less of a factor since a specified turn angle rather than a specified torque is used (RCSC 2009).

2.4.3. Calibrated Wrench Pretensioning

Calibrated wrench pretensioning (Figure 2-8) has been commonly used for many decades and is considered one of the longer lived standards for bolt installation.

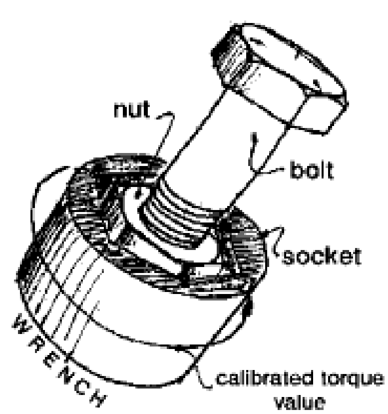


Figure 2-8. Calibrated wrench pretensioning

In a typical application, a wrench is calibrated such that the wrench is stalled (in the case of an air impact wrench) or stopped automatically (in the case of an electrically or hydraulically powered wrench) when the required pretension is reached. Since it is a torque-controlled method, many variables could result in an inadequately tightened bolt. Thus, this method is only valid if the installation procedures are adequately calibrated.

The calibration can be performed with a calibrating device, usually the Skidmore-Wilhelm bolt tension tester or using other similar devices. The Skidmore-Wilhelm tester is similar to a hydraulic load cell that can be used to calibrate an impact wrench to achieve a specified tension. The Iowa DOT requires initial rotational capacity testing of the contractor’s installation equipment to be used and performs correlation of the manual torque wrench with the calibration of the installation equipment.

In spite of its popularity over many years of use, the RCSC recognizes that the calibrated wrench pretensioning approach can be susceptible to error due to known and understood variability; therefore, more emphasis has been placed on requirements and pre-installation verification that are needed to obtain a correct clamping force in a connection. The inspection requirements given in the RCSC specification mainly consists of routine observation and monitoring of the preinstallation verification testing to ensure that workers follow the proper installation procedures. The RCSC specification stipulates that a representative sample of not fewer than three fastener assemblies be selected and used in calibration on a daily basis (RCSC 2009). Wrenches must also be calibrated when any of the following occurs:

- Any component of the fastener assembly is changed or relubricated
- Significant differences are noted in the surface condition of bolt threads, nuts, or washers
- Any major component of the wrench including lubrication, hose, or air supply are altered or adjusted

In order to minimize the variation in friction, connection components must be protected from weathering conditions such as dirt and moisture as required by the RCSC. Once removed from proper storage, there should be minimal time between wrench calibration and installation of the components.

2.4.4. Twist-Off-Type Tension-Control Bolt Pretensioning

Twist-off-type bolt tightening requires the use of tension-control (TC) bolts and a specially designed wrench (typically electrically powered) that contains a two-part socket (or chucks). A typical assembly consists of a TC bolt with a spline end, which extends below the threaded portion of the bolt, and a suitable nut and a washer as shown in Figure 2-9.

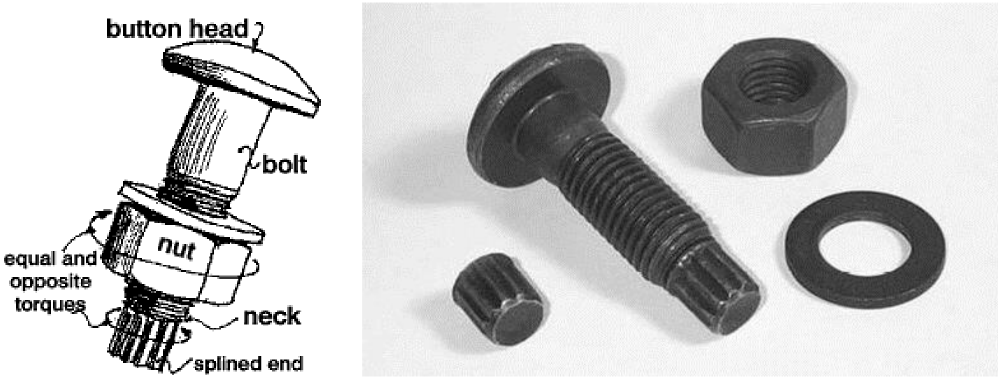


Figure 2-9. Typical tension-control bolt

This method utilizes features that indirectly indicate tension (e.g., prior to installation, calibration is required so that when a designated tension is reached by turning the nut, the spline end will be sheared off). In general, two steps are involved during installation (Tan et al. 2005): compact the joint in a snug-tight condition without damaging the splined end and systematically twist off the splines with the special wrench to achieve the prescribed tension. During the pretensioning process (Figure 2-10), one chuck in the wrench holds the bolt from the nut end and applies torque to the nut, while the other chuck grips the spline section manufactured into the bolt shank and applies a counter torque to separate the splined end from the body of the bolt.

Figure 2-10. Twist-off-type installation procedure

The installation should systematically progress from the most-rigid part of the joint to the least-rigid part to minimize the interactive effect in which the tension in a fastener may be altered by the tightening of an adjacent fastener (Tan et al. 2005).

Preinstallation verification and inspection are required to ensure that the connection has an adequate clamping force and that the ends are properly sheared off during the installation (RCSC 2009). In addition, the RCSC specification stipulates that because of the torque-based system, bolt assemblies must be used in as-received, cleaned, lubricated condition; re-lubrication in the field is not allowed. While this method offers an easy one-side installation and a quick visual inspection if installed correctly, some disadvantages include the following:

- TC bolts are generally more expensive than conventional high-strength bolts
- Requires special wrenches and additional clearance may need to be included for wrench access
- Sheared splined ends need to be properly disposed of for safety
- Deterioration of bolt threads may change the torque-tension relationship

2.4.5. Direct-Tension-Indicator Pretensioning

A DTI is a compressible, round hardened washer-type device with protrusions on one face that allow a gap between a fastener-bearing surface and a washer. The DTI is placed within a connection so that the protrusions face a bolt head or nut, or a hardened flat washer when placed under a turned component (Figure 2-11).

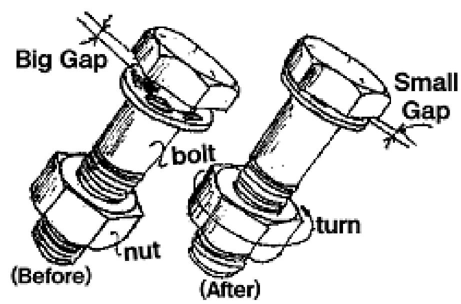


Figure 2-11. Direct tension indicator pretensioning

Once a snug-tight condition is achieved, the connection is tightened causing plastic yielding of the protrusions. During the process, the DTI is compressed to a gap that is less than the gap specified by the manufacturer’s instructions and in concert with the RCSC specification (RCSC 2009). Regardless of the torque resistance of the bolt used, the bolt tension can be evaluated by measuring the deformation of the washer (Tan et al. 2005) or a gap between the head of the bolt and the washer. A feeler gage is used to verify if the DTI has been properly compressed to an adequate gap, which is indicative of meeting a required tension. Once the gap is reduced to a prescribed amount, the bolt is considered to be properly tightened and the tightening process can stop. As the measurement of a gap is directly related to bolt pretension for a given washer, its accuracy is not affected by the bolt parameters (Tan et al. 2005). Some studies indicate accuracy ranging from 4 to 12% for parallel joints and from 11 to 23% for non-parallel joints (Bickford 1995). Note that a DTI washer can only indicate the minimum tension needed to close the gap. In the case of over tightening, DTIs are not capable of indicating the amount of over tensioning.

Also, the use of a DTI does not allow for directly monitoring bolt relaxation because the deformation of the protrusions are plastic (i.e., not returning to their original dimensions).

2.5.Preinstallation Verification

The RCSC specification requires that all fastener assemblies utilizing high-strength bolts for pretensioned and slip-critical joints be tested prior to installation (RCSC 2009). The specification states that "… Preinstallation testing shall be performed for each fastener assembly lot prior to the use of that assembly lot in the work. The testing shall be done at the start of the work. For calibrated wrench pretensioning, this testing shall be performed daily for the calibration of the installation wrench." The main purposes of the preinstallation verification are to verify the suitability of the fastener assembly and to ensure that proper installation procedures are followed by workers and that the minimum pretension is achieved during installation. Also during pre-installation verification, the installation equipment set-up is checked (e.g., compressor to be used, length of compressor hoses used, the impact wrenches, and their cut-out settings). It is critical that the condition of the bolts used in the verification testing is representative of those that are used in the actual work.

According to RCSC Section 7.2, the minimum pretension to be used in preinstallation verification should be at least equal or greater than 1.05 times that required for installation and inspection. The reason for this 105% requirement is given in the commentary, which states "… it is recognized that the pretensions developed in tests of a representative sample of the fastener components that will be installed in the work be slightly higher to provide confidence that the majority of fastener assemblies will achieve the minimum required pretension…"

Preinstallation verification testing is frequently conducted through the use of a tension calibrator. The most commonly used device is the Skidmore-Wilhelm bolt tension calibrator (Figure 2-12), while other similar devices can be used.

© 2016 Skidmore-Wilhelm

Figure 2-12. Skidmore-Wilhelm bolt tension calibrator

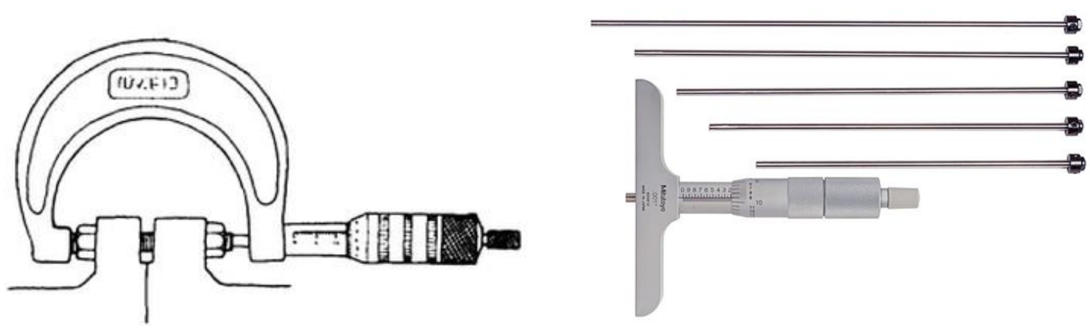
In general, a tension calibrator is used to verify that fasteners meet the minimum bolt tension requirement, wrenches are properly calibrated to achieve proper tension, twist-off-type tension-control bolts sheer off at the correct tension, protrusions of DTIs properly deform, and workers understand how to achieve the proper pretension (Skidmore-Wilhelm 2015). Typically, contract documents state that tension calibrators are required to be checked for correct calibration and re-calibrated every 12 months.

While a conventional tension calibrator can serve various purposes, its use may be limited, particularly when the bolts being tested are too short to fit into a calibration device. In this case, DTIs can be used in pre-installation verification testing as an alternative. If used for verification purposes, the DTIs must first be calibrated in conformance with the procedures outlined in the RCSC specification (RCSC 2009). However, the use of DTIs may not be a suitable option with the turn-of-nut pretensioning method. This is because the force required to compress DTIs may consume part of the turns required for the turn-of-nut procedure. When utilizing the turn-of-nut method and if bolts are too short to fit into a tension calibrator, ensuring that proper components are used in a fastener assembly and applying a required turn would be an adequate pre-installation verification.

2.6. Bolt-Tightening Verification Technologies

2.6.1. Micrometer

A micrometer is a traditional tool that can be used to measure small displacements such as bolt elongation. The micrometer is a simple hand-held device that does not require any type of computer to obtain a reading. One of the most commonly used micrometers is a C-micrometer as shown in Figure 2-13.



Bickford 2007 © 2006 Taylor & Francis Group, LLC (left) and Mitutoyo 129-132 mechanical micrometer (right)

Figure 2-13. C-micrometer (left) and depth micrometer (right)

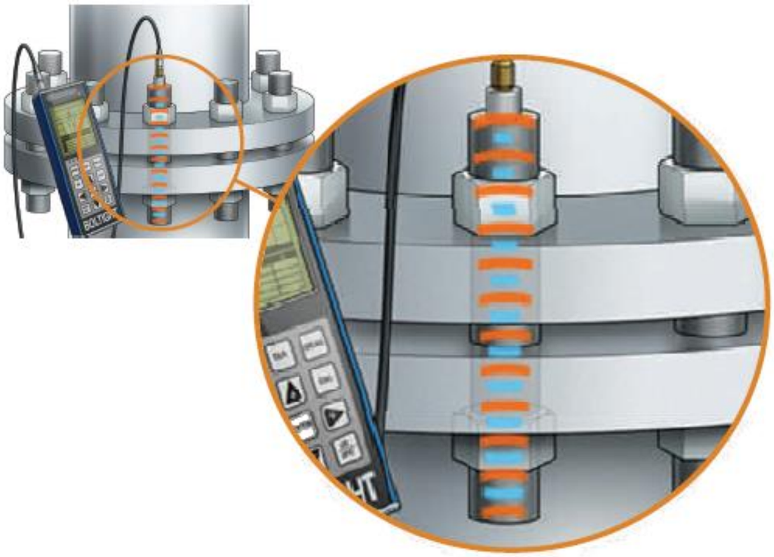
The C-micrometer requires that both ends of the bolt are easily accessible. A simple measurement of the bolt prior to tightening and then another measurement as the bolt is tightened are required to determine the amount of elongation. There is a bit of operator feel required to obtain accurate measurements using this device. It is also necessary to calculate the amount of elongation required for the bolt to reach its necessary tension (Bickford 2007).

Another type of micrometer commonly used, particularly for larger diameter bolts, is a depth micrometer (also shown in Figure 2-13). Use of the tool requires a hole to be drilled into the center of the bolt for measurement. The depth micrometer contains a loose rod that reaches down into the drilled hole. As the bolt stretches due to tightening, the loose rod does not. The operator can measure the depth that the rod goes into the bolt at the start of tightening, and then repeatedly as the bolt is tightened. Although this requires extra effort, the accuracy of a depth micrometer is usually better than that of a C-micrometer. The device also has the advantage that the operator only needs access to one end of the bolt.

Special consideration is required when the hole is drilled in the threaded portion of the bolt because the amount of stretch within this portion is different compared to the body of the bolt. Calculations are needed to determine how much elongation is required to obtain the correct bolt tension. The use of a depth micrometer also has an advantage over other measuring techniques in that residual stretch can be determined any time after installation without calibration (Bickford 2007).

2.6.2. Ultrasonic Measuring

When a bolt is tightened, two things occur simultaneously: bolt elongation and stress field formation. Stress field formation can be determined through the use of an ultrasonic device. As the stress field in a material affects the speed of ultrasound in the material, the stress in a bolt can be determined by measuring the difference between the acoustic speeds (Nassar and Veeram 2005). In a typical operation, a transducer is placed on one of the bolt ends (preferably the bolt head) to convert an electronic signal into a mechanical vibration and vice versa. An ultrasonic pulse or wave is sent down the length of the bolt (Figure 2-14), reflected off the other end, and returned to the transducer.



Boltight Ltd. 2016

Figure 2-14. Ultrasonic measuring

The measuring device attached to the transducer captures the time between the transmission of the signal and the receipt of the echo, which is referred to as the time delay. The bolt elongation due to tightening leads to an increase in the time delay. By equating the time and the acoustic velocity of the materials, the acoustic length of the bolt can be measured. Typically, the measurement needs to be taken before tightening to establish a reference length as well as after tightening so that the difference in readings can be obtained to determine the elongation of the bolt. Additional details on similar ultrasonic-based techniques are discussed subsequently.

Most ultrasonic devices available on the market utilize longitudinal waves (i.e., P waves) for the determination of clamping forces. However, attempts have been made by researchers to use the transverse waves as an additional source of information to eliminate unknown parameters such as the plastic elongation of the bolts tightened to yield (Hartmann 2007). The use of transverse waves requires special shear wave sensors as well as measuring equipment capable of handling the two independent echoes.

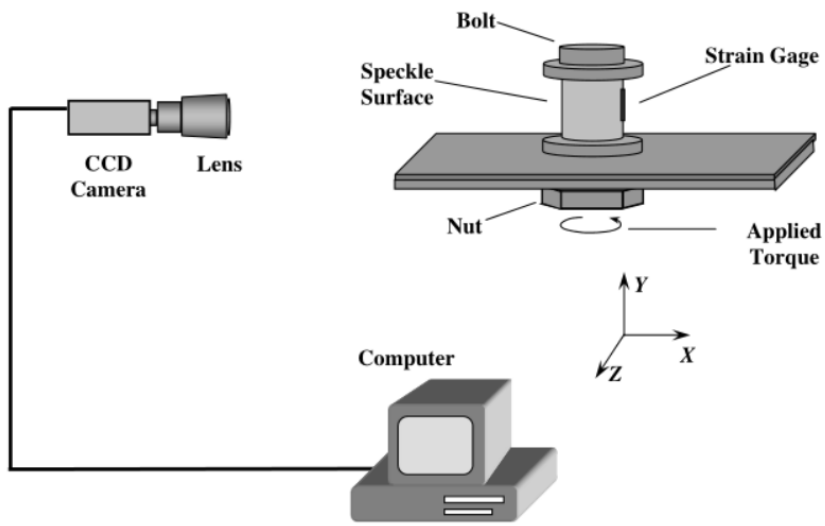
2.6.3. Strain-Based Method

Electronic resistance-type strain gages can be used to determine the tension in a bolt. Monitoring the strain and correlating it to the tension in the bolt would allow for controlling the applied force necessary to obtain the required pretension during the tightening process. Given that the strain-based measuring method would require installing strain gages to the bolt or other components of the assembly, this method may not be considered practical in a multi-fastener application. However, it is frequently used in the laboratory for research (National Instruments 2016).

Some examples of strain-based measuring tools include strain-gaged bolts and strain-gaged washers. The bolt strain can be measured by strain gages that are mounted around the shank of the bolt (strain-gaged bolt). High accuracy (±1 to 2%) in measuring bolt tension can be obtained with the use of strain-gaged bolts since the measured strain is directly related to the bolt pretension (Bickford 2007). A strain-gaged force washer, similar to a load cell, is a compressible ring with a number of strain gages mounted on it. The strain gages are usually connected using a full Wheatstone bridge configuration to provide a linear output.

2.6.4. Optical Method

Hung et al. (2006) proposed a bolt-tightening monitoring system to monitor the mechanical response of a washer placed under a bolt head using an image analysis technique known as fast digital image correlation (FDIC) as shown in Figure 2-15.

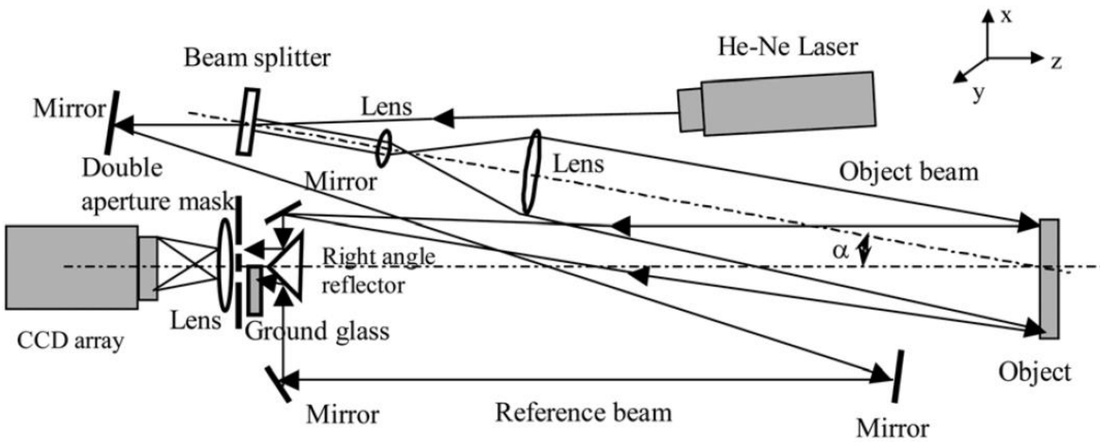


Hung et al. 2006 © 2006 American Society of Mechanical Engineers (ASME)

Figure 2-15. Typical setup for fast digital image analysis technique

FDIC is a non-contact optical method for displacement and strain measurement. This method requires the test object (washer) surface to have a random texture known as a speckle pattern, which acts as a strain sensor. Compressive strain resulting from bolt tightening is measured by analyzing the deformation of the speckle pattern of the washer. The clamping force in the connection is subsequently determined from the measured strain. This method can be performed in real-time (e.g., at video recording rate) and the measurement process takes a fraction of a second. Experiments conducted on a bolted structure with washers of different sizes have demonstrated the usefulness of this approach (Hung et al. 2006). While this method may have a potential for monitoring of clamping force during the bolt-tightening process, the strain measurement is limited to only one angular location on the washer and does not compensate for the bending effect that could be caused by the unevenness of bolt contact with the washer.

As a follow-up study, Nassar and Meng (2007) and Meng et al. (2007) proposed a digital speckle pattern interferometry (DSPI) system with a spatial phase shifting arrangement to overcome the limitation of the FDIC method. The DSPI system is also a non-contact optical method but was specifically developed for dynamic control of the bolt-tightening process by continuously monitoring the out-of-plane deformation around the surface of clamped joints as they are being tightened (Figure 2-16).



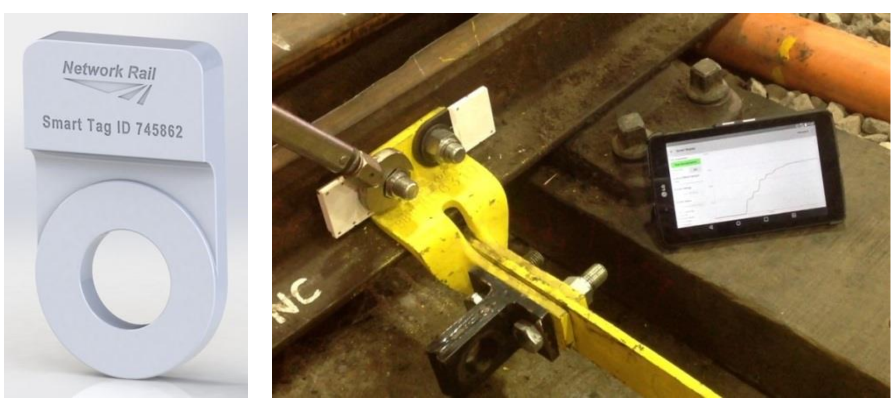
Meng et al. 2011 © 2011 American Society of Mechanical Engineers (ASME)

Figure 2-16. DSPI system for out-of-plane deformation measurement

The study utilized finite element analysis simulations to establish the correlation between clamping force and deformation. As the DSPI system is capable of providing real-time deformation information corresponding to various clamping force levels, it may have the potential for automatic control of bolted joint assembly in mass production environments (automotive assembly plants, etc.).

2.6.5. Smart Washer

In the recent past, research was conducted in the UK to develop a sensor technology that could be used in the extreme conditions associated with bolted joints in railway tracks (Tesfa et al. 2012). The main purpose of this effort was to provide a means of automatically measuring the clamping force of each individual bolted joint by using an instrumented washer. To this end, a piezo-resistive-based clamping force sensor, packaged as a smart washer with a proprietary force attenuation method, was developed (Figure 2-17).



© 2016 Smart Component Technologies Ltd.

Figure 2-17. Smart washer and data reading unit

This smart washer mainly consists of fragile piezo-resistive sensor elements and elastomers. During the development process, careful development was completed so that it is capable of the following:

- Sensing changes in the clamping force of a joint
- Providing compatibility with a large dynamic range of clamping force
- Satisfying the limitations in terms of physical size
- Providing a means of powering in situ
- Providing a solution at an acceptable cost

Numerous experiments and test results showed that the smart washer may have the potential to monitor the clamping force of bolted joints in situ (Tesfa et al. 2012). In addition, the smart washer can be integrated into a communication network necessary for automatic distribution of data.

2.6.6. Seismic Testing

Seismic testing is often used in underground mining and civil construction industries in Australia as an alternative to current practices in studying the serviceability and integrity of a bolt system (Hartman et al. 2010). The testing is performed through the use of a hammer blow and recording the resulting vibrations (Figure 2-18).

Hartman et al. 2010

Figure 2-18. Tapping device making contact with the nut of a resin bolt

The test setup requires an analog/digital convertor, a transducer, and a hammer. During testing, a transducer is held at the end of a bolt and is soft wired to an analog/digital convertor. A small hammer or an equivalent tapping device is used to induce a single blow, or pulse. The vibrations from the pulse are recorded and run through a stress wave analysis algorithm. The seismic signals are then processed by dynamic analysis to establish various criteria such as mechanical admittance, frequency spectra, and velocity. These factors are used to create an analytical model, which can be used to investigate the connectivity of the bolt to its surrounding surface. The test results are used to determine structural stiffness of the bolt with respect to the length of the bolt so that the serviceability of the bolt can be determined.

2.6.7. Magnetic Measuring

Numerous studies have shown that certain magnetic properties of a material can be directly affected by changes in the stress level (Bickford 2007). One of these properties is magnetic permeability. It may be possible to measure the bolt tension by accessing the stressed portion of the fastener and assessing the changes in magnetic permeability of the bolt during tightening. Other magnetic properties that are also known to be affected by stress level include coercive force, flux density, and hysteresis. While these properties may have the potential to be used in measuring bolt tension, no successful attempts to use these properties with bolts were identified during the literature search.

A research effort has been carried out to develop a system that utilizes magnetic waves to measure bolt pretension as well as to monitor the bolt's internal health (e.g., internal damage). One particular device is a metal strain indicator (Zagidulin and Zagidulin 2014). As shown in Figure 2-19, the device consists of a magnetic pole, a transducer, and an electronic data collection unit.

Zagidulin and Zagidulin 2014

Figure 2-19. Metal strain indicator

Similar to an ultrasonic device with the principal difference being the use of magnetic induction, the basic concept is to monitor and compare magnetic waves before and after bolt tightening and to use the difference to ascertain the deformation of a bolt caused by tightening. Unlike similar devices that require placement of a probe (sensor) on one end of a bolt, this device allows readings to be taken at any point on the bolt.

2.6.8. Acoustoelastic Method

Stress in a bolt can be measured by utilizing the acoustoelastic effect (i.e., the velocity of ultrasonic wave propagated along the bolt depends on the axial stress). As a bolt's acoustoelastic response changes with axial stress, some properties associated with the acoustoelastic response, such as ultrasound transit time and mechanical resonance, can be used to determine the axial stress level in a bolt. The time-of-flight (TOF) method, the velocity ratio method, and the resonance frequency method are the three methods that are based on these properties and are discussed in the following paragraphs.

TOF can be normally obtained by measuring the time difference between the reflecting waves in the first round trip and the second round trip. The propagation of ultrasonic waves is sensitive to both applied and residual stresses in materials. Both the direction of the applied stress and the direction and polarization of the ultrasonic waves affect the elastic wave propagation. Due to these effects, the velocities of ultrasonic waves are dependent on different stress states in the material. The stress in the bolt can be computed once the TOF under unstressed and stressed states is measured. This requires calibrating the relationship between the applied load and the change of TOF due to the load.

Yasui and Kawashima (2000) utilized a broadband normal incidence transducer in the bolt stress measurement with a 10 megahertz (MHz) longitudinal wave and a 5 MHz transverse wave that were exited and received simultaneously. A similar study conducted by Hirao et al. (2001) utilized a non-contacting shear-wave electromagnetic acoustic transducer that was used to generate and detect the shear wave propagating in the axial direction of the bolts. Both studies showed a good linear relationship between the load and the TOF or the signal phase. Since the variation of ultrasonic velocity caused by the stress change in the bolt is very small (i.e., only about tens of nanoseconds), accurate measurement of the ultrasonic velocity is critical. Jhang et al. (2006) conducted experiments that used a phase detection method for measuring TOF. During the experiments, 5 MHz ultrasonic transducers were located on the top and bottom of the sample bolts to measure the TOF. The results showed that the ultrasonic velocity decreased linearly corresponding to the stress increase and that the phase detection method produced better accuracy in measuring the TOF over other conventional methods such as a pulse-echo type technique, which is known to be sensitive to noise.

The velocity ratio method uses the difference in the acoustoelastic coefficients of longitudinal and transverse waves. Once the ratio of the TOF of the transverse wave to that of the longitudinal wave is determined, the stress in a bolt can be determined by analyzing the TOF ratio in the stressed state, only without the TOF measurement in the unstressed state (Johnson et al. 1986, Chaki et al. 2007). Kim and Hong (2009) exploited transformation between the wave modes due to stress with the purpose of calculating stress levels in high-strength bolts. This study proposed a method that utilized multiple mode-converted ultrasonic signals produced in the bolt to measure the TOF of longitudinal and shear waves. The test results revealed that the TOF ratio of two differently polarized acoustic waves was linearly proportional to the axial stress in the bolts.

The resonance frequency method is based on the hypothesis that when a bolt is stressed, both the length of the bolt and the velocity of acoustic waves change, resulting in a change in the resonant frequency, and that the frequency deviation from the resonance is a linear function of the applied stress. Conradi et al. (1974) and Heyman (1977) used a transmission oscillator ultrasonic spectrometer and a reflection oscillator ultrasonic spectrometer, respectively, to measure changes in the resonant frequency of bolts due to stress-induced elongation and change in sound velocity. Both studies used the lead zirconate titanate piezoelectric transducer to generate 5 MHz ultrasonic waves to measure the bolt stress. The experimental results showed the linearity between the frequency shift and the applied stress. A similar study by Joshi and Pathare (1984) used the carrier phase detection technique to track the frequency of the mechanical resonance of the bolts and confirmed that the frequency changed linearly with the applied stress.

3. SURVEY OF STATES AND WORKING GROUP MEETING

3.1. Survey of States

An online survey questionnaire was created and disseminated across the nation to obtain detailed information, to document practices on issues central to this project, and to help guide the research and discover new techniques. The survey asked general questions about bolt tightening, common practices used, and any new alternatives that were being considered or if respondents were aware of new bolt-tightening verification techniques under development. The questionnaire consisted of the following six questions:

1. Respondent information
2. Method of installing high-strength bolts
3. Inspection of bolt tightening
4. Equipment used to verify correct bolt tightening
5. Awareness of new techniques or technologies in bolt tightening
6. Additional comments on the subject

Questions 2 through 4 were multiple-choice and/or yes/no type questions. The respondents were also given an opportunity through questions 5 and 6 to provide comments on the subject that were not covered in questions 2 through 4.

It appears that the states or agencies with significant bolt-tightening experiences responded to the questionnaire. General conclusions were drawn from the 47 responses received. It appears that the turn-of-nut pretensioning (49%) and use of DTIs (25.5%) are the two most frequently used methods. 93.6% of the participants indicated that inspection is conducted for proper tightening regardless of the method used. Also, it was found that the Skidmore-Wilhelm bolt tension indicator is the most frequently used equipment to test for correct bolt strength and/or wrench calibration (65.4%).

The survey questionnaire and the summarized responses are given in the following. For the yes/no and multiple-choice questions, the total number of responses are given to each question or each choice in the parenthesis while exact respondent quotes are provided for questions 5 and 6.

1. *Name:*
   Company/Organization:
   Address:
   Email

2. *Which method of installing high-strength bolts is most common in your experience:*
   a. Snug-Tightened (2)
   b. Turn-of-Nut Pretensioning (23)
   c. Calibrated Wrench Pretensioning (6)
   d. Direct-Tension-Indicator (12)

    e. Tension-Control Bolt Pretensioning (Twist-Off-Type) (4)
    f. Other
        i. If Other, please explain:

3. *Do you inspect bolts for proper tightening? Yes(44)/No(3)*
    a. *If yes, which of the following methods do you inspect for following ASTM procedure? (May select more than one.)*
        i. Snug-Tightened (13)
        ii. Turn-of-Nut Pretensioning (25)
        iii. Calibrated Wrench Pretensioning (18)
        iv. Direct-Tension-Indicator (24)
        v. Tension-Control Bolt Pretensioning (Twist-Off-Type) (9)
        vi. Other
            a) If Other, please explain inspection technique:

4. *What equipment do you use to test for the correct bolt strength?*
    a. Skidmore-Wilhelm Bolt Tension Indicator (36)
    b. Direct-Tension Indicators (8)
    c. Torque Wrench (7)
    d. Tension Calibrator (4)
    e. Other
        i. If Other, please specify equipment used: Lab QA test bolt by wedge tensile test (ASTM F606)

5. *Are you aware of any emerging technology or current research in the field of high-strength bolt tightening?*
    a. MnDOT: The "Torque and Angle Fastening System" looks promising to me.
    b. Caltrans: (1) ASTM F1136 coatings on ASTM A490 bolts (and nuts and washers to complete the assemblies) - we used Dacromet and Geomet coated products on a contract, and I have answered questions from other engineers using these coatings on other projects. (2) On the bay bridge we have experienced brittle failure of ASTM 354 grade BD bolts that were galvanized. Hydrogen embrittlement appears to be the cause and investigations have been carried out pursuant to the incident.
    c. Maryland State Highway Administration: Not for A325 or A490. But our state is looking at new mechanical ways of installing large high-strength bolts for Sign Foundations.
    d. UDOT: TurnaSure Turn a nut DTIs, Applied bolting squirter DTIs
    e. US Army Corps of Engineers: We have considered the use of ultrasonic bolt tensioning but the guaranteed repeatability is an issue. At USACE we also have issues with the use of squirter washers as local contractors in the Pacific Northwest have refused to use them on our jobs because of inconsistency. QA is performed by verifying turn of the nut rotation and checking job established torque after all tensioning is completed.
    f. NH DOT: TurnaSure LLC has developed a new fastener combination called Turn A nut DTI in which the hardened washer is molded as part of the nut and linked directly with the DTI into one unit. This arrangement simplifies assembly by having the fastener as one part rather than three separate pieces.

6. *Any additional comments you would like to make on the subject.*
   a. Caltrans: Designers and spec writers need to be fully aware of the purpose and evolution of material specs for high strength materials and not make changes without fully understanding the consequences. When in doubt stay well within the requirements of ASTM.
   b. Maryland State Highway Admin: Recommend that if you want bolts installed correct you MUST spell everything out in a well written procedure. Like the direct tension indicators but no one is going to use them due to the cost.
   c. UDOT: We do a quality assurance testing of each lot consisting of hardness, yield, tensile, wedge and rotational capacity tests. We use the Skidmore-Wilhelm for pre-installation verification testing and to verify tension on installed bolts with 0.005 in. feeler gage supplied by the DTI manufacturer.
   d. AL DOT: Several issues with high strength bolting after tightening checks from my experience, most are not common, but I have seen all of these at least once:
      i. Bolts not being at least flush with the nut after tightening, even with the correct length detailed in the shop drawings and the correct length installed. (Contractor was required to replace any bolts which were not at least flush with the nut with longer bolts.)
      ii. Removal of drift pins after erection of girders; some contractors struggle with this.
      iii. Diaphragms and splice plates not lining up due to fabrication errors.
      iv. The manual torque wrenches used for tightening spot checks are too easy to adjust. The operator can inadvertently adjust the tension setting while using. My inspectors and the contractor record the setting after using the Skidmore-Wilhelm prior to beginning spot checks. This setting is checked frequently to ensure the setting remains correct.
      v. Bolts not being torqued to the correct tension requirements or not at all. In this case, the entire splice is checked with the manual torque wrench. (This is not required by ALDOT specification. This is something I have adopted as a deterrent for a contractor not doing their QC prior to my inspectors doing the spot checks. After checking 200 or more bolts in a single splice with a manual wrench, the contractors personnel are more likely to make sure all the bolts are torqued.)
      vi. Using the wrong length bolts, this is usually caught visually. Any bolts that have a projection of more than 1/4 (more than 3 threads) out of the nut or are not at least flush with the nut should be investigated to ensure the bolt lengths are correct. The bolts which are not flush are always replaced with a longer bolt. A projection of more than a 1/4 from the nut could cause jamming (the nut has reached the unthreaded portion of the bolt prior to reaching tensioning requirements). I would advise to consult with the detailer/designer if this problem occurs to verify if jamming is possible. These comments provided by one of our project engineers representing ALDOT.
   e. NH DOT: Just to be clear, NHDOT specifies the use of direct tension indicators (DTIs) for the installation of high strength fasteners for structural connections. Our installation specs follow nationally accepted practice requiring proper storage of fasteners, proper snugging of the connection, daily calibration using the Skidmore-Wilhelm as part of the installation routine. In addition, NHDOT requires waxing the bolt threads and nut face with a paraffin wax at the time of fastener installation. Inspection after installation is

performed visually and with the use of feeler gage. NHDOT does not allow the use of "Squirter" DTI's.

f. Vermont Agency of Transportation: Vermont only allows the use of DTIs for high-strength bolts. The only exception to this is tension control is allowed when dome headed high-strength bolts are specified. Vermont switched to exclusive use of DTIs about 3 years ago. Previous to that all of the above were allowed.

3.2. Working Group Meeting

A number of people/organizations within Iowa State University (the Institute for Transportation, the Ames Laboratory, the Center for Nondestructive Evaluation, etc.), the Iowa DOT, the Iowa consulting engineering community, and the Iowa contractor community may have knowledge related to improving the state-of-the-practice with respect to bolt-tightening verification. To facilitate discussion and brainstorming between these resources and other interested parties, a working group meeting was held at the Institute for Transportation October 12, 2015. The main goals of the meeting were to identity existing bolt-tightening verification technologies including those not readily utilized and to brainstorm new means and methods (e.g., instruments with innovative metallurgical properties) that may have potential to be developed and/or implemented if additional research were to be conducted.

To guide the search for potential alternatives and technology development, the topic of bolt tightening was discussed with Iowa DOT engineers and other professionals who have experiences. The following paragraphs present a summary of the discussion.

The demand is high for a device that can be used to determine the stress within a bolt in the field. By determining the stress, it is possible to calculate the tension within the bolt. For example, in structural steel connections, any pretensioned joint requires that the bolt within the connection meets a specified pretension. Currently, there are a few different ways to determine/estimate this stress. However, it seems that the accuracy of these determinations/estimations is the most challenging aspect of developing a device, especially in light of the variation in bolt sizes, types, and connection configurations.

The technique that seems to be the most likely candidate for further development would use ultrasound waves to measure the change in bolt length (using time-of-flight). Today, there are simple handheld products that utilize ultrasound waves for the purpose of bolt tightening and verification. The devices are small enough to be used in tight conditions in the field. The downfall is the uncertainty in terms of accuracy for using them in a variety of situations, with bolts whose exact initial length is not known, and interpretation of results when "notable" amounts of stick-out is present. Thus, the devices currently on the market may be useful for approximate results (e.g., distinguishing that the pretension is significantly off from the desired value). However, for critical conditions where accuracy is needed with little to no error, the devices may fall short without further calibration.

In regards to developing new technology, consideration can be given to the possibility of employing magnetics. A positive aspect of this potential is the simplicity of creating a magnet and establishing a handheld device. As with the other devices, however, the obstacles to overcome would be to ensure accuracy. Strict calibration standards would need to be designed so that the device can adjust to different metal types, bolt sizes and types, and connection configurations. Even with the obstacles in place, it is agreed that the potential is there along with the market demand.

Another potential concept that may warrant further investigation is to develop an enhanced system that measures the strain in the bolt. Such a concept might consist of the insertion of a wire into the middle of the bolt, which could be calibrated to measure the bolt strain and then used to estimate the stress and/or load in the stressed portion of the bolt.

4. CONCLUSIONS

The main objectives of this project were to explore high-strength bolt tightening and verification techniques and to investigate the feasibility of developing and implementing new alternatives. A literature search and a nationwide survey were conducted to collect and review information on various bolt-tightening techniques such that an understanding of available and under-development techniques could be obtained. Also, the requirements for materials, inspection, and installation methods outlined in the RCSC specifications (2009) were reviewed and summarized.

The technology review effort presented herein was intended to seek a methodology or techniques that, in the near or long term, can be used to quantitatively and accurately determine the stress level in bolted connections. This required a preliminary evaluation of currently available technologies that either have been proven in the laboratory or appear to have potential for bolt stress measurement.

One area explored was non-destructive evaluation (NDE) technologies. NDE techniques have been used frequently in industry and research laboratories to evaluate structural components for internal stress or metallurgical conditions without interfering with the integrity of the material or its suitability for service. Over the past several years, a number of specific advances have been made in NDE that may provide solutions to help meet the purpose of future research. During the course of this study, numerous NDE techniques were reviewed and preliminarily evaluated. Unfortunately, many of the reviewed methods appeared unsuitable for field application of bolt-tightening verification. For example, some methods use complex and expensive equipment that are normally used in a controlled laboratory environment, while other techniques were intended for a single specific purpose and may not be suitable as a general bolt stress inspection technique. More importantly, many reviewed NDE techniques appear to be simply not applicable to measuring bolt stress. Therefore, only a few select NDE techniques that either have been used by other industries or may have some measure of future potential in bolt-tightening verification were presented in this report. Table 4-1 presents a summary of some of the reviewed NDE techniques and their applicability to bolt-tightening verification.

Table 4-1. NDE techniques and their applicability to bolt-tightening verification

NDE	Strength	Limitations	Applicability
Acoustoelastic	Capable of bolt damage detection; suitable for automation	High sampling rate required; noise sensitive	maybe
Electromagnetic	Some test probes do not require direct contact with the part inspected; detects surface and near surface defects; minimum part preparation; suitable for automation	Depth of penetration limited; wire coils needed; high skill and training needed; reference standards needed for setup	maybe
Magnetic	Rapid inspection; low cost; suitable for automation	Complex sensor electronics may be required; surface preparation needed	maybe
Optical	Fast; remote	Requires heavy equipment; limited to laboratory environment; sensitive to noise and vibration	maybe
Piezo-electric impedance	High sensitivity to local structural damage; large frequency bandwidth	Better suited for dynamic environment	maybe
Piezo-resistive sensing	Easy to implement; based on resistance measurement; low frequency; small circuit area	Sensitive to noise at low load	yes
Radiography	Can be used in virtually all materials; high resolution and sensitivity; ability to inspect complex shapes without disassembly; minimum part preparation	Extensive operator training and skill required; access to both sides of part normally required; expensive; possible radiation hazard	no
Strain-based	Various sensor types available; proven accuracy in other applications	Difficult to attach to a bolt	yes
Ultrasonic	Most widely accepted and commercially available; easy to interpret and convenient; enhanced sensitivity; only one side access needed; minimum part preparation required	High sampling rate required to improve accuracy; skill and training needed; surface finish and roughness may interfere with inspection; reference standards often needed	yes

The conclusions and discussion gleaned from the literature review, survey, and working group meeting, as well as the research team's preliminary evaluation on select NDE techniques follows:

- The survey and literature review showed that all methods recognized by the RCSC are currently being utilized although some are more popular than others. The nationwide survey revealed that the most frequently used methods are turn-of-nut and DTI pretensionings. The use of tension-control bolts appears to be increasing. The Skidmore-Wilhelm tester appears to be the most commonly used device for wrench calibration.

- Reviewing the procedures for bolt installation in fields outside of structural engineering revealed that the same methods (i.e., turn-of-nut, calibrated wrench, DTIs, and tension-control bolts) are often used by other industries.

- While the torque control method offers relatively easy tightening control and operation, its high sensitivity to the friction properties of an assembly may limit the reliability of this method in critical applications. The angle control method offers more consistent pretension that is less affected by friction. However, care needs to be taken during the installation process to minimize the possibility of over tightening. The use of bolt heaters does not appear to be practical in steel construction, as it may alter the mechanical properties of the adjacent components. In addition, it requires a higher level of operator awareness, as well as time to allow the bolt to properly cool.

- Among some of the installation methods used in other industries, the use of a hydraulic tensioner appears to provide relatively better accuracy over other methods. This is due to the fact that the tension developed in a fastener is directly related to its change in length. However, the use of this method is limited when the position of the connection does not allow for a hydraulic tensioner to be utilized because of its size and also the need for a pressure source.

- A micrometer or a caliper can be useful for direct measurement of bolt elongation. However, this may not be suitable for civil engineering applications given that, in many instances, the bolt elongation is very small and difficult to measure and also that both sides of the bolt may not be accessible.

- In most piezoelectric impedance methods, a damage index can be used to assess the degree of tightness or looseness of bolts. However, it appears very difficult to quantitatively determine the bolt stress using this method.

- Use of a standard resistance strain gauge or piezo-resistive-type sensor embedded or mounted to a bolt allows an effective measurement of bolt strain. Instrumenting the sensor to the body of a bolt seems challenging. Some commercially available products (e.g., smart sensor, smart bolt) have been used by other industries.

- Although fiber-optic sensors (e.g., fiber Bragg gratings or FBGs) have been frequently used in structural health monitoring applications, the use of FBGs for bolted connections is rarely reported. Because of their advantages, including proven accuracy in other applications and electromagnetic immunity, fiber-optic sensing technologies appear to have some measure of potential to be used for real-time monitoring of bolt tension, especially when high electromagnetic interference is expected in the field. The multiplexing capability of FBGs is another advantage if a large number of bolts need to be monitored simultaneously.

- Ultrasonic NDE techniques appear to be one of the most accepted methods used for pretension verification purposes. These techniques allow for investigating the clamping force during and after bolt tightening. Some studies showed that the concurrent use of longitudinal and transverse waves in principle provides a better solution to determine the stress of bolts without disassembling the joint. However, the general concept currently used to describe the bolt stress as a function of the time delays of ultrasonic waves may need further refinement (e.g., using second order equations) to increase the accuracy.

- While some tools and methods are available that can be used to verify the tension developed in a bolted connection, it appears as though many of them are still research-based and that the accuracy of the methods identified during the literature review has not been fully validated. Therefore, further research is recommended.

There is merit to seeking an improved methodology within the area of automated, refined data analysis and sensor improvements. Future research efforts may be needed toward more in-depth investigation of the most useful NDE techniques followed by development of a new alternative that can be used for verifying bolt tightening with proven accuracy.

Examples of such techniques would be ultrasonic-based techniques and strain-based or piezo-resistive-based methods, as these technologies seem to possess positive characteristics including inherent cost-effectiveness and simplicity.

The research team recommends that these technologies be validated through rigorous experiments and augmented with refined analytic approaches. The future research should include a full demonstration of the method, definition of performance limitations, and engineering parameters such as features and component size, orientation, accessibility, and operating limits.

An emphasis should be placed on improved verification reliability, cost-effective validation, and transferability to a range of applications. In addition, the future research program should explore and apply new engineering approaches to develop quantitative inspection and verification techniques that are much faster, less costly, and that result in a newly developed or improved technology that is more flexible and easily managed in treating the diversity of the issues associated with bolted connections.

Once complete, the new alternative would result in the installation of safer and more reliable connections. It would serve as a pivotal technology in the efficient management of the Iowa DOT’s transportation assets.

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