

High Strength Bolt Tightening and Verification Techniques for Steel Connections: In-Depth Study and National Survey

Yoon-Si Lee^{1,*}, Brent Phares²

Abstract

The current means and methods of verifying that high strength bolts have been properly tightened is 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 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 and verification 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 Research Council on Structural Connections specifications were reviewed and summarized. The technology review effort presented herein was intended to seek a methodology or techniques which, in the near or long term, can be used to quantitatively and accurately determine the stress level in bolted connection. This required a preliminary evaluation of currently available technologies, including numerous nondestructive evaluation techniques that either have been proven in the laboratory or appear to have potential for bolt stress measurement. This paper summarizes all of the work completed during this project.

Keywords: High strength bolt; tightening; verification; pretension.

INTRODUCTION

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 function safely.

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The current means and methods of verifying that high strength bolts have been properly tightened is 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 there exist a few studies that reviewed these technologies [1, 2], compilation and in-depth evaluation of such techniques are limited. 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.

HIGH STRENGTH BOLT TIGHTENING

There are currently five techniques recognized by the Research Council on Structural Connections (RCSC) as suitable for installing high strength bolts in the United States [3]:

1. Snug-tightened,
2. Turn-of-nut pretensioning,
3. Calibrated wrench pretensioning,
4. Twist-off-type tension-control bolt pretensioning,
5. 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 independent of the others. The installation requirements can be found in Sec. 8 of the RCSC [3]. 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 [4]. In addition, the criteria for proper inspection of bolted joints can be found in Sec. 9 of the RCSC [3].

Snug-tightened

Snug-tight is commonly known as “ordinary effort of worker using a spud wrench” or “the first impact of an impact wrench.” 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” [3]. 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 tested, with the rotational capacity lot number to ensure that the same combination of tested elements are used together during their field installation.

Snug-tightened joints are frequently found in shear or tension type connections where a 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 [3].

Since a specified pretension is not required for snug-tightened joints, its 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 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 [3]. 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), one needs to check all fasteners in that connection, tighten and re-inspect all bolts or nuts.

Turn-of-nut Pretensioning

Turn-of-nut pretensioning (Figure 1) is based on the application of a specific minimum elongation as a means of controlling the pretension of high strength bolt. 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. 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 1. 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.

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 $\frac{1}{3}$ turn is depicted in Figure 1. It is important to note that proper installation depends upon joint compactness and securely holding the bolt head while the nut is turned.

The following summarizes its general procedures:

1. Bring the assembly into firm contact and apply full effort with a spud wrench or apply a few impacts with impact wrench until 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 did not rotate in the splice), and the end of the bolt with a single straight line;
3. Apply the prescribed turn (Table 1) 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 [3].

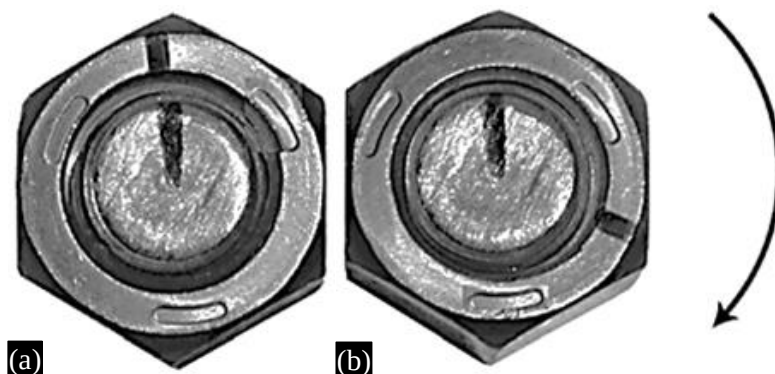


Figure 1. Turn-of-nut pretensioning [5] (a) mark bolt, nut and steel plate, and (b) desired position achieved ($\frac{1}{3}$ turn illustrated).

Table 1. Nut rotation from snug-tight condition for turn-of-nut pretensioning^{a,b} [2].

Bolt length ^c	Disposition of outer faces of bolted parts		
	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

^aNut 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;

^bApplicable only to joints in which all material within the grip is steel;

^cWhen the bolt length exceeds $12d_b$, the required nut rotation shall be determined by actual testing in a suitable tension calibrator that simulates the conditions of solidly fitting steel;

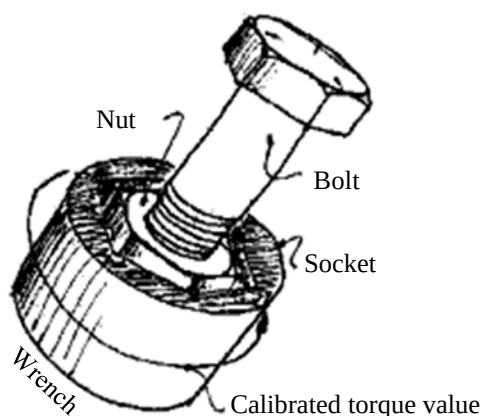
^dBeveled washer not used.

Calibrated Wrench Pretensioning

Calibrated wrench pretensioning (Figure 2) has been commonly used for many decades and is considered one of the longer lived standards for bolt installation. 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, there are many variables that 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.

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 preinstallation verification that are needed to obtain a correct clamping force in a connection. The inspection requirements given in the RCSC Specifications mainly consist of routine observation and monitoring of the preinstallation verification testing to ensure that the workers follow the proper installation procedures. The RCSC Specifications [3] stipulates that a representative sample of not fewer than three fastener assemblies be selected and used in calibration on a daily basis. Wrenches must also be calibrated when:

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

**Figure 2.** Calibrated wrench installation [6].

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 the wrench calibration and the installation of the components.

Twist-off 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 3. 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: Compacting the joint in a snug-tight condition without damaging the splined end; and systematically twisting off the splines with the special wrench to achieve a prescribed tension. During the pretensioning process (Figure 4), one chuck in the wrench holds the bolt from the nut end and applies torque to the nut, while at the same time 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. 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.



Figure 3. Typical tension controlled bolt [7].

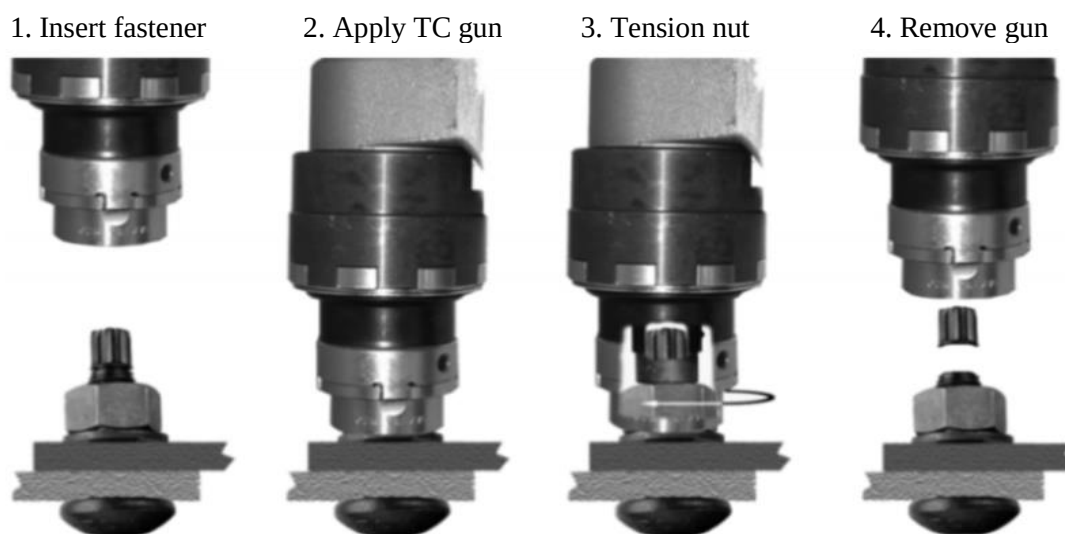


Figure 4. Twist-off-type installation procedure [5].

Preinstallation verification and inspection are required by the RCSC to ensure that the connection has an adequate clamping force and that the ends are properly sheared off during the installation [3]. In addition, the RCSC Specifications stipulates that because of its 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, there are some disadvantages including:

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

Direct-tension-indicator Pretensioning

DTI is a compressible, round hardened washer-type device with protrusions on one face that allows a gap between a fastener bearing surface and a washer [8]. The DTI washer is placed into a connection so that the protrusions are faced against a bolt head or nut, or against a hardened flat washer when placed under a turned component (Figure 5). 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 [3]. Regardless of the torque resistance of the bolt used, the bolt tension can be evaluated by measuring the deformation of the DTI 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. Some studies indicate that the accuracy ranged from 4% to 12% for parallel joints and from 11% to 23% for non-parallel joints [9]. It is important to note that a DTI washer can only indicate the minimum tension needed to close the gap. In the case of over tightening, it is 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 is plastic (i.e., not returning to its original dimensions).

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 [3]. 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

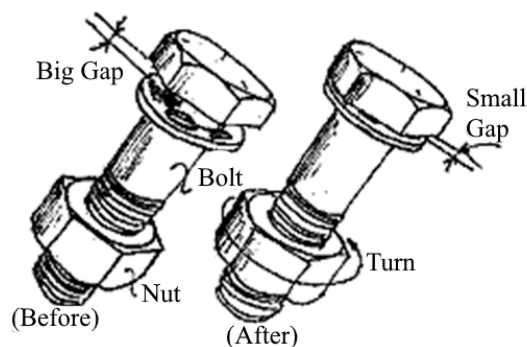


Figure 5. Direct tension indicator pretensioning [8].

minimum pretension is achieved during the installation. Also during the preinstallation 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 tester while other similar devices can be used. In general, a tension calibrator is used to determine if fasteners meet the minimum bolt tension requirement; if wrenches are properly calibrated; if twist-off-type tension-control bolts shear off at a proper tension; if protrusions of DTIs properly deform; and if workers comprehend how to achieve the proper pretension [10]. It is required that a tension calibrator be checked and re-calibrated yearly.

BOLT TIGHTENING VERIFICATION TECHNOLOGIES

Micrometer

A micrometer is a traditional tool that can be used to measure small displacement such as bolt elongation. It 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. This device 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 measurement using this device. It is also necessary to calculate the amount of elongation required for the bolt to reach its necessary tension [11].

Another type commonly used particularly for larger diameter bolts is a depth-micrometer. It requires a hole to be drilled into the center of the bolt for measurement. The tool 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 to be put into the procedure, the accuracy of a depth micrometer is usually better than that of a C-micrometer. It also has the benefit of the operator only needing access to one end of the bolt. Special consideration must be taken 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 must be made to determine how much elongation is required to obtain the correct bolt tension. The use of a depth micrometer has an advantage over other measuring techniques as the residual stretch can be determined any time after installation without calibration [11].

Ultrasonic Measuring

When a bolt is tightened, two things occur simultaneously: bolt elongation and stress field formation, which can be determined through the use of an ultrasonic device. As the stress field in a material would affect the speed of ultrasound in the material, the stress in the bolt can be determined by measuring the difference between the acoustic speeds [12]. In a typical operation, a transducer is placed on one of the bolts ends (preferably the bolt head) to convert an electronic signal into a mechanical vibration and vice versa. An ultrasonic pulse or a wave is sent down the length of the bolt (Figure 6) [13], reflected off the other end and returns to the transducer. 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 its acoustic velocity of the materials, its acoustic length can be measured. Typically, the measurement needs to be taken before the tightening to establish

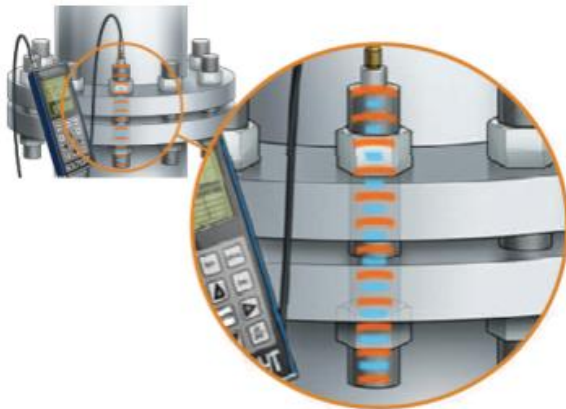


Figure 6. Ultrasonic measuring [13].

a reference length as well as after the tightening so that the difference in readings can be obtained to determine the elongation of the bolt.

Most ultrasonic devices available in 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 [14]. The use of transverse waves requires special shear wave sensors as well as measuring equipment capable of handling the two independent echoes.

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. As the strain-based measuring method would require installing strain gages to the bolt or other components of the assembly in consideration, this method may not be considered practical in a multi-fastener application. However, it is frequently used in laboratory for research purpose [15]. 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 ($\pm 1\%$ 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 [11]. A strain-gaged force washer, similar to a load cell, is a compressible ring with a few number of strain gages mounted on it. The strain gages are usually connected as a full Wheatstone Bridge to provide a linear output.

Optical Method

Nassar et al. [16, 17] proposed a digital speckle pattern interferometry (DSPI) system with spatial phase shifting arrangement. The system is 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 (Figure 7) as they are being tightened. 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 environment (e.g., automotive assembly plants, etc.).

Smart Washer

In the recent past, research was conducted in the U.K. to develop a sensor technology that could be used in the extreme conditions associated with bolted joints in railway track [18]. The main purpose of this effort was to provide a means of automatically measuring the clamping force of each individual bolted joint by means of an instrumented washer. To this end, a piezo-resistive based clamping force

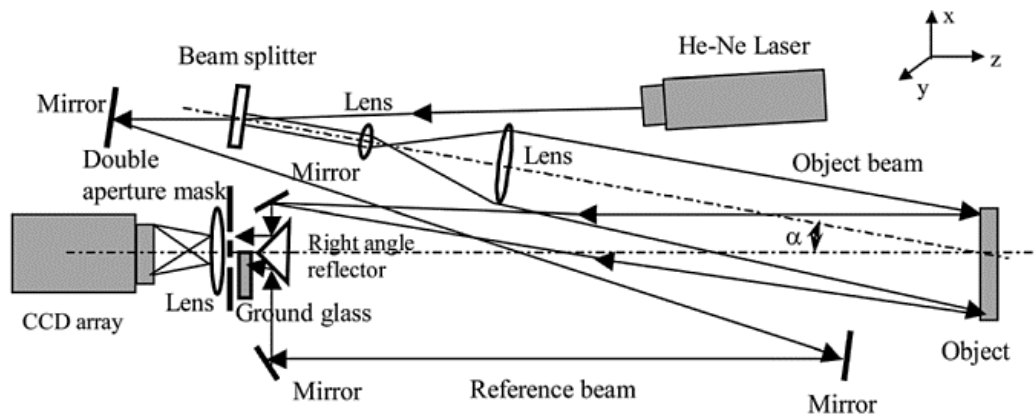


Figure 7. Schematic of DSPI system for out-of-plane deformation measurement [19].



Figure 8. Smart washer and data reading unit [20].

sensor, packaged as a “smart washer” with a proprietary force attenuation method was developed (Figure 8). This smart washer mainly consists of fragile piezo-resistive sensor elements and elastomers. During the development process, careful considerations were given so that it is capable of:

1. Sensing changes in the clamping force of a joint;
2. Providing compatibility with a large dynamic range of clamping force;
3. Satisfying the limitations in terms of physical size;
4. Providing a means of powering in situ;
5. 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 [19]. In addition, the smart washer can be integrated into a communication network necessary for automatic distribution of data.

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 [21]. The testing is performed through the use of a hammer blow and recording the resulting vibrations. The test setup requires an analogue/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 analogue/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 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.

Magnetic Measuring

It has been proven by numerous studies that certain magnetic properties of a material can be directly affected by changes in the stress level [11]. One of such 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 potential to be used in measuring bolt tension, no successful attempts to use these properties in 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 (i.e., internal damage, etc.). One particular device is a metal strain indicator [22]. The device consists of a magnet pole, a transducer, and an electronic data collection unit. Similar to an ultrasonic device with the principal difference being the use of magnetic induction, its 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 other 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.

SURVEY AND WORKING GROUP MEETING

Survey of States

An online survey questionnaire was created and disseminated across the nation to obtain detailed information and 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 were being considered or if respondents were aware of new bolt tightening verification techniques under development.

It is believed that the states or agencies with significant bolt tightening experiences have responded to the questionnaire. General conclusions were drawn from a total of 47 responses that were received. It appears that the turn-of-nut pretensioning (49%) and the 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%).

Working Group Meeting

There are a number of organizations/engineering communities that 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 with the main goals of the meeting being: (1) to identify existing bolt tightening verification technologies including those not readily utilized; (2) to brainstorm new means and methods (e.g., instruments or materials with innovative metallurgical properties, etc.) 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 the Iowa Department of Transportation engineers and other professionals with relevant experiences. The following paragraphs present a summary of the discussion.

There is a high demand 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, a 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 which could then be used to estimate the stress and/or load in the stressed portion of the bolt.

SUMMARY

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 were reviewed and summarized.

The technology review effort presented herein was intended to seek a methodology or techniques which, in the near or long term, can be used to quantitatively and accurately determine the stress level in bolted connection. 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 frequently used in industry and research laboratories to evaluate structural components for internal stress or metallurgical condition 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 the purpose of the future research. During the course of this study, numerous NDE techniques have been 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 some 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 industry or may have some measure of future potential in bolt tightening verification were presented in the previous section. Table 2 presents a summary of some of the reviewed NDE techniques and their applicability towards bolt tightening verification.

Table 2. 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	M
Electromagnetic	Some test probe 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	M
Magnetic	Rapid inspection; low cost; suitable for automation	Complex sensor electronics may be required, surface preparation needed	M
Optical	Fast, remote	Requires heavy equipment, limited to laboratory environment; sensitive to noise and vibration	M
Piezo-electric impedance	High sensitivity to local structural damage, large frequency bandwidth	Better suited for dynamic environment	M
Piezo-resistive sensing	Easy to implement, based on resistance measurement, low frequency; small circuit area	Sensitive to noise at low load	Y
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	N
Strain-based	Various sensor types available, proven accuracy in other applications	Difficult to attach to a bolt	Y
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	Y

*Given in alphabetical order; **Y: Yes; **N: Not likely; **M: Maybe.

CONCLUSION

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

- It was found from the survey and the literature review 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 the turn-of-nut and DTIs 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, tension-control bolts) are often used by other industries.
- While the torque controlled 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 would not allow for a hydraulic tensioner to be utilized because of its size and the need of 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 application since, in many instances, the bolt elongation is very small and difficult to measure and 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, etc.) have been used by other industries.
- Although fiber optic z.
- While there are some tools and methods 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 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 ultrasonics 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 nation's transportation assets.

REFERENCES

1. Kumar S, Mahto D. Recent Trends in Industrial and other engineering applications of NDT. *International Journal of Scientific & Engineering Research*. 2013;4(9):183-13p.
2. Wang T, Song G, Liu S. Review of bolted connection monitoring. *International Journal of Distributed Sensor Networks*. 2013;(2):1-9p. doi:10.1155/2013/871213
3. RCSC Committee A1. Specification for Structural Joints using High-Strength Bolts. Research Council on Structural Connections (RCSC). 2020. Available from: <https://www.aisc.org/globalassets/aisc/publications/standards/a348-20w.pdf>
4. AISC. Steel Construction Manual, 15th ed. American Institute of Steel Construction (AISC). 2017.
5. Structural Bolts. Fastenal Company. Available from: <http://www.fastenal.com>
6. AISC and RCSC Calibrated Wrench or Torque Installation. Applied Bolting Technology. Available from: <http://www.appliedbolting.com>

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7. Twist-off Bolts. Applied Bolting Technology. Available from: <http://www.appliedbolting.com>
 8. Direct Tension Indicators. Applied Bolting Technology. Available from: <http://www.appliedbolting.com>
 9. Bickford JH: Introduction to the Design and Behavior of Bolted Joints, 3rd ed. Marcel Dekker. 1995.
 10. Skidmore-Wilhelm. Available from: <http://www.skidmore-wilhelm.com>
 11. Bickford JH: Introduction to the Design and Behavior of Bolted Joints, 4th ed. CRC Press. 2008.
 12. Nassar SA, Veeram AB. Ultrasonic control of fastener tightening using varying wave speed. Journal of Pressure Vessel Technology. 2005;128(3):427-6p. doi:10.1115/1.2218347
 13. Echometer Ultrasonic Measurement. Boltight Ltd. Available from: <http://www.boltight.com>
 14. Harmann G. Potentials and limitations of ultrasonic clamp load testing. SAE Technical Paper 2007-01-1668. SAE International. doi:10.4271/2007-01-1668
 15. Measuring Strain with Strain Gages. National Instruments. Available from: <http://www.ni.com>
 16. Nassar SA. Optical monitoring of bolt tightening using 3D electronic speckle pattern interferometry. Journal of Pressure Vessel Technology. 2007;129(1):89-95. doi:10.1115/1.2389024
 17. Meng A, Yang X, Nassar S. Effect of bearing friction and hole clearance on the clamp load-deformation correlation in bolted joints, Journal of Materials and Manufacturing. 2007;(116):699-706. doi:10.4271/2007-01-1670
 18. Tesfa B, Horler G, Al-Thobiani F, Gu F, Ball AD. A clamping force measurement system for monitoring the condition of bolted joints on railway track joints and points. Journal of Physics: Conference Series. 2012;364(1):1-16. doi:10.1088/1742-6596/364/1/012021
 19. Meng A, Nassar S, Templeton D. A novel optical method for real-time control of bolt tightening. Journal of Pressure Vessel Technology. 2011;133(6):61211-61215. doi:10.1115/1.4004797
 20. The Smart Ecosystem. Smart Component Technologies Ltd. Available from: <http://smartcomptech.com/ecosystem>
 21. Hartman W, Lecing B, Higgs J, Tongue D. Nondestructive integrity testing of rock reinforcement elements in Australian mines. 2010 Underground Coal Operators' Conference. University of Wollongong & the Australasian Institute of Mining and Metallurgy. 2010. p.161-10p.
 22. Zagidulin R, Zagidulin T. Nondestructive Evaluation steel bolts and studs tightening effort in casing power plant equipment using the metal strain indicator IN-01m, 11th European Conference on Non-Destructive Testing (ECNDT 2014). Curran Associates, Inc. 2014: p. 2553-5p.