Improved pretensioning procedures for anchor bolt connections in sign, luminaire, and traffic signal structures

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

MnDOT, along with numerous other state departments of transportation (DOTs), are finding that anchor bolt nuts are coming loose at a concerning rate for overhead signs, luminaire, and traffic signal (SLTS) structures. Anchor bolts are critical to the structural stability of a structure, since, for MnDOT, they are the only connection to the foundation. Re-tightening loose nuts imposes a significant drain on state DOT resources. More importantly, the loosening of these nuts increases fatigue stresses on the anchor bolts, possibly increasing the risk of failure.

Loose anchor bolt nuts were recorded on both old and new structures, some immediately after installation. In addition, even after retightening by MnDOT maintenance personnel, anchor bolt nuts were found to come loose within two years. The pre-tension force developed in anchor bolts during nut tightening is critical to keeping them sufficiently fastened to the structure and foundation. Anchor bolts loosening after installation and maintenance suggested a deficiency in MnDOT's previous anchor bolt pre-tensioning procedures.

To alleviate the anchor bolt pre-tensioning limitations, new specifications were developed in a previous study titled Re-Tightening the Large Anchor Bolts of Support Structures for Signs and Luminaires. The new specifications were developed through laboratory testing, field monitoring, surveys of current practices, and finite element modeling.

This project focuses on the implementation and improvement of the previously proposed specifications. For a specification to be effective, constructability is critical; if the procedures cannot feasibly be performed in the field, they will likely not be utilized to the fullest extent. Previously proposed specifications were attempted on a variety of MnDOT SLTS structures. Both new installation and maintenance practices were investigated. Monitoring on a previously

instrumented in field cantilevered overhead sign structure was also continued as part of this study. The performance and behavior of anchor bolts along with changes to the specification were studied in the laboratory. Finally, improved procedures were recommended based on the field and laboratory work.

During implementation, difficulties were discovered with the proposed procedures. Clearance is a critical aspect for many lighting and traffic signal structures; a wrench cannot be effectively placed inside the base to property pre-tension the anchor bolts in many cases. During pre-tensioning, individual steps from the specifications often needed clarification and tended to be difficult to follow. After investigating structures pre-tensioned with the new specifications, none had loose anchor bolt nuts, likely indicating that the new procedures are effective.

A laboratory testing regimen was derived from the field experience and structural monitoring. Two fatigue tests were completed, one replicating field stresses and the other replicating AASHTO typical fatigue stresses. Relaxation of the anchor rods and lubrication properties were studied in the laboratory. Lab testing indicated that the primary mechanism of pretension loss in properly tightened anchor rods is likely due to relaxation, and not fatigue loading. In addition, accurate pretensioning should be performed with force controlled methods like torque or DTI washers, since displacement based turn pretensioning can result in a high degree of error. Lubrication impacts the final pretension when using torque based pretensioning, but is fairly consistent as long as the same class of lubricant is used.

Overall, the proposed procedures were found to be effective, but sometimes difficult to perform and sometimes not feasible for certain SLTS structures. The improved procedures focus on force controlled pretensioning and an immediate relaxation retightening.

CHAPTER 1: INTRODUCTION

1.1 Background

Across the United States, various state departments of transportation (DOTs) are finding that the base anchor rod nuts on critical support structures for traffic signals, overhead signs, and high mast light towers are coming loose. Re-tightening loose nuts imposes a significant drain on state DOT resources. In addition, the loosening of these nuts increases the failure risk of tall and overhanging structures.

In many of the Minnesota DOT's (MnDOT's) observed cases, anchor rod nuts were loose immediately after installation. Even after tightening by MnDOT personnel, it was found that anchor bolt nuts had consistently come loose just two years after re-tightening.

To alleviate the issue, new specifications were developed in a prior study. The new specifications were created around the importance of lubrication, bringing the nut to snug tight, turn-of-nut tightening, and tightening order.

After development in the laboratory, the new recommended specifications still needed field verification to ensure constructability and in-service efficacy. If the specifications are not able to be effectively implemented, anchor rod loosening will continue unabated.

1.2 Report Organization

This report consists of multiple chapters, each focusing on a different aspect of the overall project. The basic content of each chapter is as follows:

- Chapter 2 contains a literature review of various anchor rod tightening properties along with a review of current specifications.
- Chapter 3 includes the results from implementation of the laboratory specifications. It is divided into implementation on overhead sign structures and on lighting and traffic signal structures given the distinct differences in the two procedures.
- Chapter 4 summarizes the results of monitoring data from a cantilevered sign structure in Minneapolis, Minnesota.
- Chapter 5 covers the laboratory testing in the Iowa State University structures laboratory.
- Chapter 6 brings all aspects of the project together, recommending changes to the specifications and providing concluding results.

1.3 Background of MnDOT Typical Anchor Rod Connections

To transfer forces on their overhead signs, lighting, and traffic signal (SLTS) structures to foundation bases, MnDOT employs double nut connections on anchor rods cast into a concrete foundation (Figure 1.3.1).

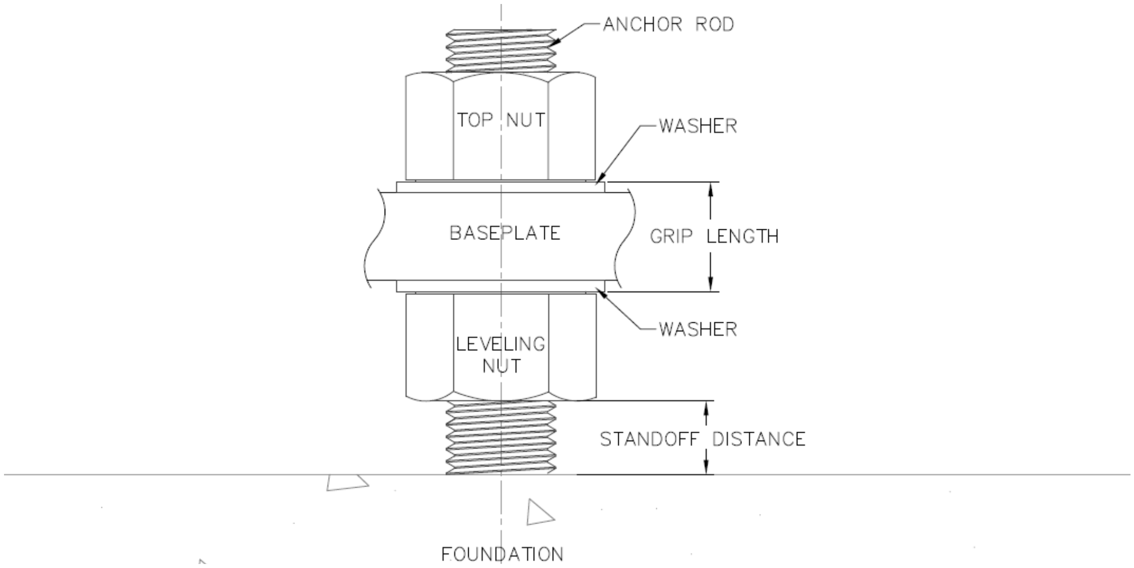
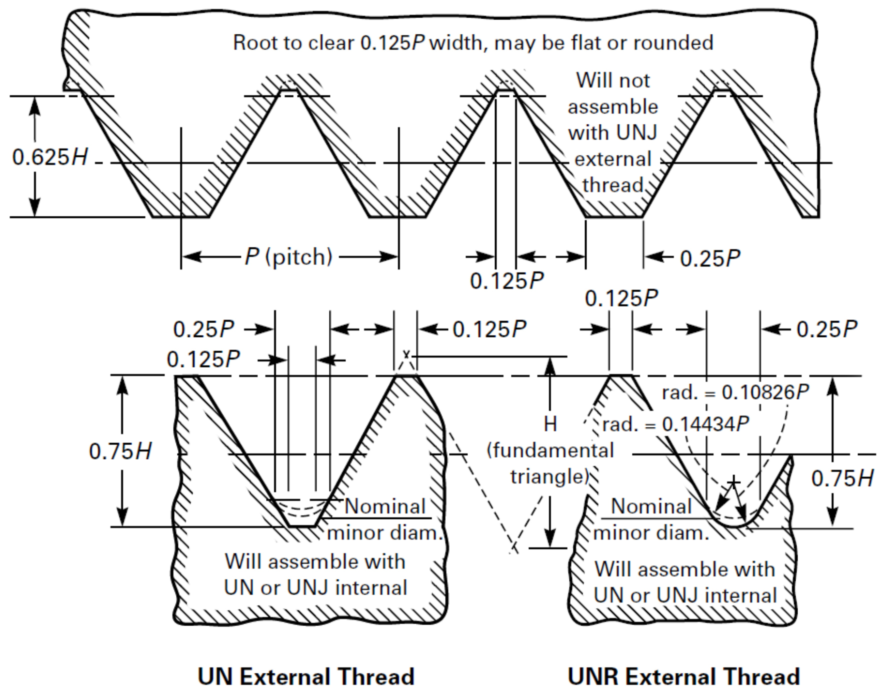


Figure 1.3.1. Typical double nut anchor rod connection

The connection is comprised of an anchor rod that clamps the baseplate of a structure with two nuts—commonly referred to as top and leveling. The leveling nut (on the bottom) is for leveling the structure before installation, and the top nuts are generally for tightening. Clamping force generated by tightening the top nut secures the baseplate of the structure in place. The thickness of the baseplate plus both top and bottom washers is referred to as the grip length, which is the length that the anchor bolt carries tension resulting from tightening plus external loads (dead load, wind load, etc.) during service.

1.3.1 Geometry

Typical anchor rod dimensions and materials are covered here before covering procedures. In the United States, the typical anchor rods utilized for SLTS structures adhere to the ASTM F1554-18 specification (ASTM 2014). Note that this specification differs from ASTM 325 and 490 for structural steel bolts. Anchor rods can be specified in three different yield grades: 36, 55, and 105 ksi. Of these, Grades 55 and 105 are most frequently used by MnDOT. Threads are cut or rolled according to ANSI/ASME B 1.1 Class 2A, as outlined in Figure 1.3.2.



ASME 2005

Figure 1.3.2. Typical anchor rod dimensions, UN threads

Additionally, permanent grade identification is required on the ends of the anchor rods. As shown in Figure 1.3.3, marking can be completed with color coding or, if required, die stamped markings.

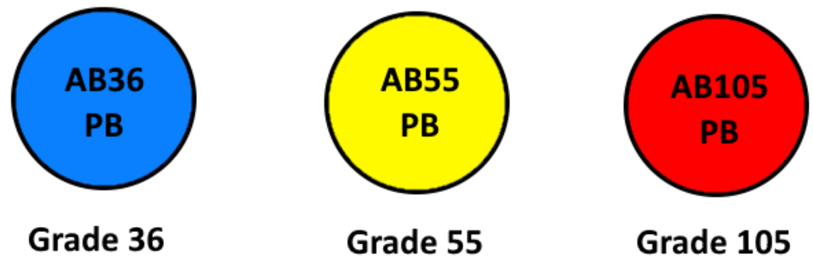
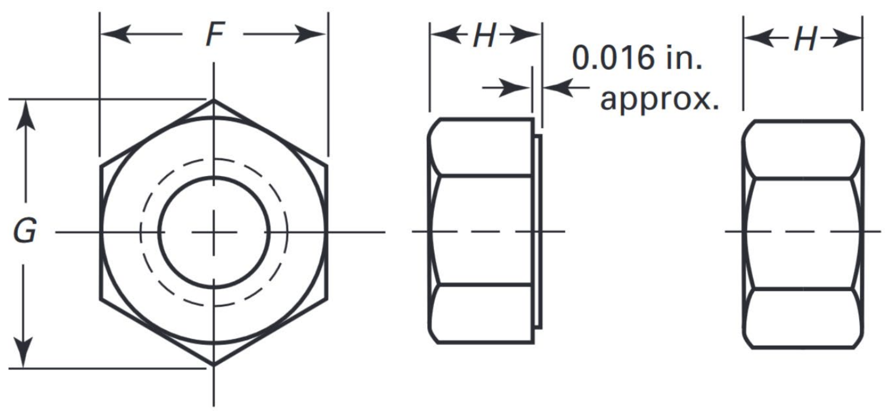


Figure 1.3.3. Typical anchor rod top coloring or stamped markings

As of 2018 construction specifications, MnDOT requires permanent markings (MnDOT 2018). Typical Nuts are ASTM A563 grade DH or A194 grade 2H Heavy Hex, which follows the dimensions of ANSI B1.1 Class 2B, as shown in Figure 1.3.4.



ASME 2010

Figure 1.3.4. Typical heavy hex nut dimension variables

Nuts have a proof load stress of 150 ksi (ASTM 2015 and 2005, ASME 2010). Finally, washers are specified to ASTM F436-18 (ASTM 2018).

1.4 Specifications from Previous Research Project

This implementation project was based on a previous study funded by MnDOT titled Re-Tightening the Large Anchor Bolts of Support Structures for Signs and Luminaires (Chen et al. 2018). The previous project tested anchor rod tightening properties in the laboratory, instrumented an overhead sign for field monitoring, developed finite element models (FEMs) for numerical analysis, and developed new tightening specifications based on the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (LRFD – SLTS) 5.17.5.2 (2015).

The new specifications developed through the previous project were primarily based on AASHTO LRFD - SLTS 5.17.5.2, but with primary changes to torque, in addition to turn-of-nut verification, defining snug tight, and taking into account grip length. All three changes were a direct result of laboratory testing and literature review. By adding these three items, the new specifications aimed to take out inconsistency and better verify correct installation. The new specifications included an eight-step verification sheet, a table with the corresponding installation information (Table 1.1), and a table with wrench lengths for bringing nuts to snug tight. The eight steps are as follows:

1. Verify F1554 anchor bolt grade is as specified for the project. Verify nuts are ASTM A563 heavy hex and washers are F436.
2. Verify anchor bolts are clean and not damaged and plumb – not more than 1:40 slope or 1/4" in 10". (If bolts are out of plumb or damaged, contact project engineer.)

3. Lubricate anchor bolts with MnDOT-specified bridge grease (within 24 hours of tensioning) and turn nut down to foundation. Lubricate bearing surfaces of leveling nut and top nut prior to tightening.
4. Level leveling nuts – make sure nuts are less than one anchor bolt diameter from the foundation but no less than 1-1/4" for overhead (OH) signs.
5. Install structure with an F436 washer below and above baseplate and snug top nuts. When snugging, use snugging torque or maximum open-end wrench length on both the top nut and the leveling nut following the star pattern. Two cycles of snugging shall be performed prior to Step 6.
6. Perform turn-of-nut tightening. Mark the nuts and adjacent baseplate and turn the minimum required turn per appendix, but do not exceed the verification torque.
7. Confirm verification torque was achieved, or continue to turn nut until verification torque is achieved.
8. 48 hours after initial tightening, apply re-tightening torque. The re-tightening torque is 110% of verification torque ($1.1 \times T_v$).

Table 1.1. Example of torque turn specification sheet with OH sign anchor bolts and grip lengths

Pole Type	Anchor Bolt Ø	Bolt Type (Galvanized to Spec. 3392)	Baseplate Thickness	Snug Torque (ft-lbs)	Rotation Beyond Snug	Verification Torque, T_v (ft-lbs)	Re-Tightening Torque, T_r 48 Hours After Tightening
Type 5-7 Sign Truss	2-1/2 Inch	Type B Grade 55 Spec. 3385.2B	2 Inches	550	1/12	3,300	3,630

Table 1.1 is a shortened example of the new table provided for MnDOT specifications from the previous project. In the full table, there are 17 different types of structures and 22 different overall installation types. The full Table 1.1 that was provided to MnDOT was intended for contractors as a reference to find the correct values for a particular installation and to work through the eight steps defined above.

The previous project also completed a thorough literature review of current tightening practices along with a survey of various states' tightening procedures (Chen et al. 2018). Based on the prior study, 88% of states with tightening specifications used some form of turn of nut, with eight states lacking any specifications for tightening. Many states used multi-step specifications such as AASHTO LRFD - SLTS 5.17.5.2, going through lubrication, snug tight, and specified turns.

While states may not have common tightening procedures, one thing they did have in common was loose anchor rod nuts. Of 29 states, 80% reported having loose nuts on 1% to 90% of their structures with many states reporting that the deficiencies were due to contractor error and inconsistent practices. For the four states in the survey that reported no loose nuts on their structures, their procedures were different; however, two of them had fairly rigorous contractor verification and inspection to ensure proper pre-tension. Other states that reported loose nuts and subsequently implemented more rigid specifications experienced a decrease in "loosening" of the anchor rod connections, but noted that the specifications were costly and time intensive to implement.

CHAPTER 2: LITERATURE REVIEW

This literature review focused primarily on bolted connections in SLTS structure bases. Where limited information was available for double nut connections in civil engineering applications, applicable research from the mechanical and aerospace engineering industries was utilized. In addition, the terms “bolt” and “anchor rod” are not used interchangeably unless discussing a fundamental property. The term “rod” refers to ASTM F1554, while the term “bolt” generally refers to bolts in structural steel connections (usually ASTM 325, 490, or ISO 261(Metric)) and not foundation connections. Finally, clamping force developed in threaded fastener connections is referred to as “pre-tension,” since it is the same terminology as bolting specifications from the structural steel industry. Note that unlike concrete structures, “pre-tension” in this case refers more to the general case of pre-stressing, i.e., inducing a stress into a structure to resist applied loading, and not stressing the member before placement as is commonly used with precast, pre-tensioned, concrete beams.

2.1 Importance and Brief Research History

In the US, concerns about anchor rods in SLTS structures, and particularly cantilevered overhead sign structures (COSSs), arose in the late 1980s and 1990s. Around 1990, several states experienced collapses of COSSs with one recorded fatality (Culp et al. 1990, James et al. 1997, Kaczinski et al. 1998) During the 1990s, fatigue provisions for SLTS structures was studied and summarized in the National Cooperative Highway Research Program (NCHRP) Report 469: Fatigue-Resistant Design of Cantilevered Signal, Sign, and Light Support Structures (Kaczinski et al. 1998). This research went into revising and writing the fatigue provisions in AASHTO

LRFD – SLTS. The anchor rod tightening procedures in AASHTO LRFD - SLTS 5.17.5.2 were derived from the Federal Highway Administration's (FHWA's) anchor rod guidelines (Garlich and Thorkildsen 2005), which were derived from several other research projects (Till and Lefke 1994, Johns and Dexter 1998, Dexter and Ricker 2002).

In 2014, the Alaska Department of Transportation and Public Facilities (DOT&PF) looked into the loosening problem and found that the pre-tension loss was likely due to localized yielding of the anchor rods, but no conclusive evidence could be found (Hoisington and Hamel 2014). It is likely other states also experienced loosening before the investigation by Alaska.

Finally, in 2018, the previous study for this project was published (Chen et al. 2018). This study quantified tightening requirements from AASHTO and recommended tightening procedures to MnDOT for greater fatigue loosening resistance.

For the importance of proper pre-tensioning, or at least tensioning beyond snug tight, Kaczinski et al. (1998) notes that, when a connection loses pre-tension past the snug-tight condition, it will put more stress on surrounding anchor rods and can lead to wedging of the structure. These actions increase fatigue stress on anchor rods, reduce stiffness in the connection, and lead to failures within the grip length of anchor rods (Dien 1995). Garlich and Thorkildsen (2005) assert that: "When a pre-tensioned joint is subject to cyclic fatigue loads, it acts as if the pieces pressed together were actually monolithic (i.e., the bolts themselves feel only about 20% of the load range), with the majority of the load range transferred through the faying surfaces. When a bolted joint is not properly pre-tensioned, all the load is transferred through the bolts and they may quickly fail by fatigue." As long as a connection is beyond snug tight, there will be lower stresses on the anchor rods, and they will be less likely to fail in fatigue.

In addition to the fatigue loading issues, loose anchor rods present a serviceability problem (Hoisington and Hamel 2014, Chen et al. 2018, Phares et al. 2016). Loose anchor rod nuts cause state DOTs to expend resources on retightening and inspection, with the costs then passed on to the taxpayer.

2.2 Anchor Rod Pre-Tensioning

The four primary methods for anchor rod pre-tensioning are angle-based, torque-based, direct pre-tensioning, and thermal methods. Direct pre-tensioning is generally achieved with a jack and is not covered due to the design and clearance limitations. Tightening can also be completed with a combination of torque and turn. In the aerospace and mechanical engineering industries, computerized wrenches are utilized in critical connections (Bickford 1997). These are also not discussed as many systems are proprietary and not widely used by contractors. Finally, thermal tensioning methods are not covered due to difficulties with field implementation.

2.2.1 Torque-Controlled Pre-Tensioning

Torque controlled pre-tensioning is a force controlled method where the applied torsion on a nut is correlated to the estimated pretension force developed in the threaded fastener. The general governing equation for torque-controlled pre-tensioning is Equation 2.1, where T is the torque required to be applied to the connection, F is the final clamp or pre-tension force, D is the diameter of the anchor rod, and K is referred to as the "nut constant."

$$F = \frac{T}{KD} \tag{2.1}$$

Almost all torque-controlled procedures depend on a variation of Equation 2.1 given the high degree of empiricism with torque-controlled pre-tensioning.

The nut factor, *K*, is empirical and fairly variable. A brief list of variables on which the nut factor depends is presented by the Research Council on Structural Connections (RCSC) in their 2014 Specification for Structural Joints Using High-Strength Bolts as follows:

- Finish and tolerance on the bolt and nut threads
- Uniformity, degree, and condition of lubrication
- Shop or job-site conditions that contribute to dust and dirt or corrosion on the threads
- Friction that exists to a varying degree between the turned element (the nut face or bearing area of the bolt head) and the supporting surface
- Variability of the air supply parameters on impact wrenches that results from the length of air lines or number of wrenches operating from the same source
- Condition, lubrication, and power supply for the torque wrench, which may change within a work shift
- Repeatability of the performance of any wrench that senses or responds to the level of the applied torque

This list represents the known fact that many factors come into play with torque-controlled pre-tensioning. In most cases, it is recommended that nut factors be developed for specific individual installations or wrenches directly calibrated to desired pre-tension with a bolt calibration device. Additionally, many specifications have variations on *K* that are based primarily on frictional coefficients for a set type of bolt.

According to the RCSC, variations in final bolt pre-tensions can vary on the order of +/- 40% when uncontrolled pre-tensioning with torque control is utilized (RCSC 2014). Bickford (1997), in An Introduction to the Design and Behavior of Bolted Joints*,* notes that "torque control of preload has obvious limitations and dangers, but in most cases, it will be the only practical or economical choice." Bickford also asserts that "success in this case [bolt pre-tensioning], is not 'preload accuracy'; it's 'joints which don't fail.'" Both of these cases illustrate a generally agreed upon fact in the bolting community that torque control is easy and economical to use, but it is fairly empirical, requiring proper verification and testing.

2.2.2 Angle/Turn-Controlled Pre-Tensioning

Unlike torque control, which is based primarily on force-controlled tightening, angle-based tightening is displacement-based. The turn process treats the threads on a rod as an inclined plane that is advanced as the nut is turned. As the threads are advanced, the anchor rod stretches a predetermined amount. Under most circumstances, turn control generally results in less final pre-tension scatter than torque (as noted by Bickford 1997, AASHTO 2015, James et al. 1997, Kulak 2002, and Fisher and Struik 1974, among others). For structural steel bolting, much of the uncertainty decrease is due to a yielding procedure, which is covered later in the specification review section. Equation 2.2 is one relationship between turn and pre-tension force.

$$F = \frac{C\alpha P_i AE}{L} \tag{2.2}$$

Much like the torque-pre-tension equation, many different codes use different variables or coefficients, but the underlying displacement principle is the same.

In Equation 2.2, F is the final pre-tension or clamp force, L is the length of the bolt in the grip length, and C is a ratio of bolt stiffness to connection stiffness. E is Young's modulus, P_i is the pitch factor (slope of the threads i.e. for an 8 TPI rod the pitch factor would be 1/8), and A is the tensile area of the fastener. Finally, α is the nut turn angle in ratio of a full turn (i.e., 1 is a full turn and 1/6 turn would be 0.1667).

For Equation 2.2 to be valid, the connection must be in firm contact, which is often referred to as the snug-tight condition. The pre-tension that is associated with snug tight is generally about 10% of the yield point of the anchor rod, and it is reached by an empirical method or a specified torque. Snug-tight is the initial condition for the anchor rod pre-tensioning with turn control. If the fastener is kept in the elastic range, there can be uncertainty from scatter in the snug-tight condition. Because turn is displacement based, the grip length and connection stiffness are also critical factors that must be taken into account.

2.3 Pre-Tension Control and Verification

Outside of approximating pre-tension with torque or turn control, there are several methods for verifying or checking pre-tension dirctly. The technology in this section is primarily based on Investigation of High-Strength Bolt-Tightening Verification Techniques (Brent Phares et al. 2016) and An Introduction to the Design and Behavior of Bolted Joints (Bickford 1997). Both of these sources contain numerous other references, but for brevity's sake a summary is presented here.

The two methods of verifying pre-tension in this section are representative of accepted and field-implementable solutions for anchor rod pre-tension verification. Other methods that were investigated were strain gauges (vibrating wire, resistance, and optical), permanent load cells/sensing washers, acoustoelastic measurement, tension indicating rods, twist-off connectors, elongation measurement, and magnetic wave detection. These other options were not pursued further because implementation would not likely be feasible or cost effective for the current project. Additionally, many of the methods had greater uncertainty than widely used standards.

2.3.1 Direct Tensile Indicating Washers

A relatively simple and accepted method of directly indicating tension in a bolted connection is with a direct tensile indicating (DTI) washer. Almost all bolting codes have a provision for DTI washers and there are several ASTM International standards for them. Traditional DTI washers have rounded, raised bumps or dimples on their surface. During pre-tensioning, the dimples plastically deform as they are compressed. Deformation increases the surface area of the dimples, requiring more load to deform further due to fundamental material properties.

To check the pre-tension, a feeler gauge is utilized to measure the gap between the DTI washer and the baseplate, which can then be correlated directly to the force required to flatten the DTI to its respective thickness. Additionally, DTIs can be calibrated with a known force to produce a specific pre-tension for a certain flattening. The error for these washers is about 10%, which is relatively low when compared to torque- or turn-controlled pre-tensioning. However, DTI installations require both contractor and inspector training on proper procedures and use of feeler gauges. Also, the clearances and design limitations of SLTS bases may limit the accessibility of DTI washer use.

There are also squirter-type DTIs that eject a colored polymer once the dimples are deformed to the specified pre-tension. This type of DTI must be specifically manufactured for one type of bolt and a single pre-tension. Although squirter-type DTIs make for easier installation and inspection, they are currently only produced for structural steel bolts and not for anchor rods.

2.3.2 Bolt/Rod Tension Calibrators

Bolt tension calibrators, while not part of the final installation, serve an important part of the anchor rod pre-tensioning process. In many specifications, if torque is used for pre-tensioning, a tension calibration of the installation will be required at least daily. Tension calibrators, themselves, are a sort of load cell, and commonly a hydraulic-based design.

The calibrators measure a given load and can be approximately correlated back to the torque required to tension the connection. They can also be used to calibrate DTI washers for a predetermined flattening in relation to a desired pre-tension force. Turn-of-nut calibration is somewhat limited, though, because the stiffness of the bolt calibrator will likely not match the true connection stiffness that it is supposed to be replicating. Error in the tension calibrators is in the range of 2–5%, but is not indicative of the final pre-tension accuracy since the tightening tools or measurement devices are being calibrated on it, and it does not remove the inherent inaccuracies with various tightening methods.

2.4 Pre-Tension Loss in Bolted and Anchor Rod Connections

Much like many other aspects of threaded fastener connections, there is a high level of uncertainty, empiricism, and disagreement when considering connection loosening mechanisms. In this review, an overview of losses is presented in two sub sections: service loading and relaxation. The service loading section covers pre-tension loss from fatigue and dynamic loads with a brief review of loosening theory. Relaxation covers stress loss from immediate and long-term relaxation of anchor rods.

2.4.1 Pre-Tension Losses from Service Loading

Much like anchor rod pre-stressing, pre-tension loss in threaded fastener connections is fairly empirical and difficult to accurately predict, with many confounding variables. Overall, there are generally three accepted loosening conditions: axial loading, transverse loading, and combined (Bickford 1997). In SLTS structures, the forces in the anchor rods are primarily axial. Base shear forces causing transverse loading on anchor rods also occurs to varying degrees in SLTS structures, but they generally are less than 10% of the axial forces induced.

While theories on loosening vary, they generally agree that proper pre-tension can prevent, or highly reduce, loosening, and that transverse loading is generally the most detrimental for bolted connections. Note that the majority of loosening research has been conducted on bolted connections, not double nut foundation rods, so extrapolation of results, especially from transverse loading, is approximate.

The majority of bolted connections in the structural steel and, for that matter, other industries are designed for fastening two or more pieces of material together. For this reason, a majority of testing and standard testing procedures are focused on the transverse loosening condition. In general, the majority of pre-tension loss in transverse loading appears to occur when the “slip” condition is reached (i.e., the frictional force holding the plates together is overcome by the applied load, making the plates slip). There are many theoretical causes for this loosening (Rodriguez Lopez et al. 2018, Bickford 1997, Jiang et al. 2003), but it is difficult to definitively prove any one theory. The Junker vibration tester (Junker 1969) is an accepted standard for testing the loosening behavior of bolted connections under transverse loading (DIN 2015).

Axial load loosening has also been studied to some degree, while not as intensely as transverse loosening. Most sources agree that, if a threaded fastener is pre-tensioned to 20% beyond the anticipated fatigue loading, there will be little to no loosening (Fisher and Struik 1974, Bickford 1997). In axial loading, for pre-tension loss, compression cycles will be the most damaging, since they can essentially remove the net pre-tension from the connection, resulting in less resistance to possible transverse shear loads and nut turning. The primary fatigue loosening mechanism of pure axial loading is generally theorized as localized plastic yielding of threaded connections, which decreases the elongation and pre-tension of the fastener (Hoisington and Hamel 2014, Bickford 1997). In a study of high mast light towers (HMLTs) in Alaska, local plastic yielding was the primary loosening mechanism cited (Hoisington and Hamel 2014).

2.4.2 Pre-Tension Losses from Relaxation

Much like other materials under constant loading, there will be some degree of immediate and long-term relaxation and creep for anchor rods after pre-tensioning. The AASHTO LRFD – SLTS currently recommends that connections are retightened 48 hours after original pre-tensioning. From several sources (Fisher and Struik 1974, Bickford 1997, Yang and Dewolf 1999, Nijgh 2016, Till and Lefke 1994), total preload loss for high strength bolts will be in the range of 5 to 50%, depending on many factors. Additionally, pre-tension loss is a time-dependent process and generally follows a log-power pattern no matter the degree of loss.

One major source of loss stems from the thickness of the galvanized coating (Yang and Dewolf 1999). After 42 days, Yang and Dewolf found that the total relaxation of 7/8" A325 high-strength bolts was about 5% for uncoated bolts and 20% for bolts with a 20 mil (0.020 in.) galvanized coating. Embedment of the galvanizing surfaces is also a critical factor along with the grip length and bolt diameter (Nijgh 2016). Nijgh found that a lower grip-length to bolt-diameter ratio, which is typical of MnDOT double nut connections, led to greater pre-tension losses. This behavior was due to the increased stiffness of the bolts and higher pre-tension levels, leading to increased plate embedment and creep. Retightening for anchor rods is generally recommended in the first 2 to 5 days, which represent approximately 90% of the total lifespan pre-tension losses due to the power distribution of loss (Munse 1967, Fisher and Struik 1974, Yang and Dewolf 1999). Overall, relaxation likely occurs primarily due to localized yielding, creep, and relaxation of the surface finish, which may be exacerbated due to the high pre-tension forces, galvanizing, and large connection stiffness used in MnDOT's SLTS structure connection geometry.

2.5 Implementation Studies and Interviews

While there are many theoretical and laboratory-tested high-strength anchor rod pre-tensioning tests, far fewer field implementation studies exist on which to base the specifications. Previous studies often completed state and industry interviews for an inventory of anchor rod and bolt pre-tensioning practices (James et al. 1997, Chen et al. 2018, Hoisington and Hamel 2014). In the previous Phase I research study for this project (Chen et al. 2018), the researchers found that procedures varied widely from state to state, most states experienced loose nuts, and many states believed that a lack of quality assurance/quality control (QA/QC) during the original installation was the primary reason for the loosening. Both James et al. (1997) and Phares et al. (2016) received similar responses from both industry and state DOTs, respectively.

An interesting quote from Phares et al. regarding a response to their survey, from the Alaska DOT&PF, was: “Bolts [are] 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 the Alaska DOT&PF 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… the contractor’s personnel are more likely to make sure all the bolts are torqued.)”

Most literature also agrees that proper pre-tensioning of large-diameter, high-strength anchor rods is not feasible without a hydraulic torque wrench, regardless of whether torque- or tension-controlled pre-tensioning is used (Hoisington and Hamel 2014, Garlich and Thorkildsen 2005). Finally, the difficulty with documentation of installations with a few anchor rods is noted by Garlich and Thorkildsen’s 2005 FHWA report: “In addition, unless a contractor is erecting a group of sign structures, only a few high strength bolts may be needed. Where the quantity of fasteners is small, it may not be realistic to expect the same bolt documentation and testing as would be provided on a steel bridge erection project." Note that this report is referring to anchor rods of SLTS structures even though "bolt" terminology is used. When all of the previous interviews and field experience are considered, significant difficulties are seen in communicating and implementing an effective anchor rod pre-tensioning specification.

2.6 Mechanics of Pre-Tensioned Double Nut Connections

As briefly discussed in the turn-of-nut tightening section, the total displacement is based on C, or the ratio of rod to baseplate stiffness. The stresses and strains in anchor rods depend both on the baseplate and the anchor rod and can be modeled as a set of springs in parallel (Culpepper 2009). This concept is illustrated in Figure 2.6.1 with k_b representing the baseplate stiffness and k_r representing the rod stiffness.

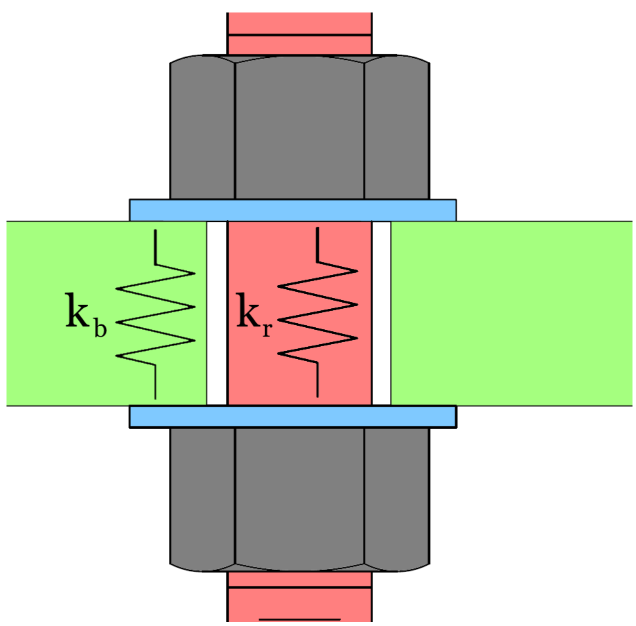


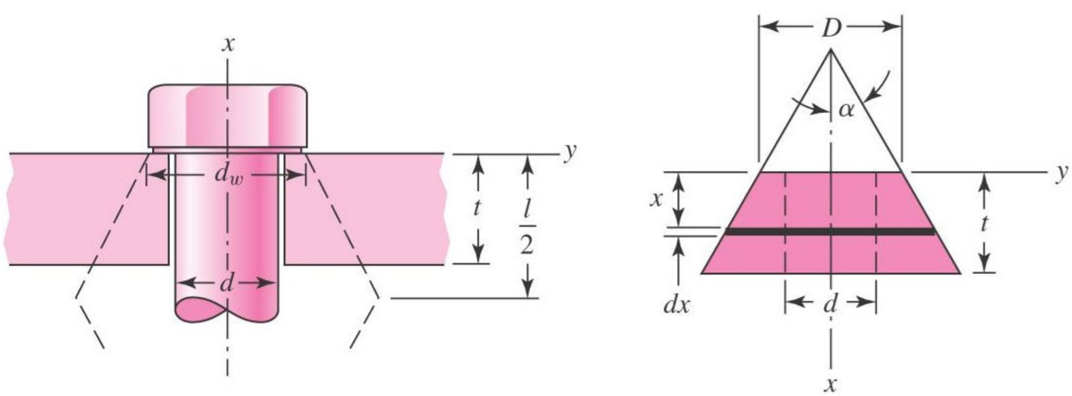
Figure 2.6.1. Double nut connection stiffness

The stiffness of the anchor rod is simply calculated with Equation 2.3 from mechanics of materials.

$$k_r = \frac{A_t E}{l_t} \tag{2.3}$$

In Equation 2.3, A_t is the tensile area of the anchor rod, E is Young's modulus, and l_t is the grip length plus 1 thread into the nut.

Stiffness of the plate must be calculated considering the stiffness distribution in the baseplate, which can be approximated as a cone, called a frusta, extending out from the exterior of the washer (Budynas et al. 2015). For a typical bolt, the stress distribution and variables are shown in Figure 2.6.2.



Budynas et al. 2015

Figure 2.6.2. Stress distribution of a typical half bolt connection

To adapt this model for a double nut connection, t would be taken as ½ of the baseplate thickness with 1 washer thickness included, and l_t would be ½ of the total grip length plus 1 thread into the nut. The aspect ratio of the stress distribution is taken as 30 degrees since this compares closely to FEM analysis (Budynas et al. 2015).

In the case of this derivation, the stiffness of the washers is included in the frusta, since they have approximately the same Young's modulus. With the washer included, the flat dimension of the heavy hex nut then becomes the *D* or *dw* (refer to Figure 2.6.2 for typical dimensions) (ASME 2010). Note that this formula does not take into account the galvanized coating due to complex creep and relaxation impacts.

Baseplate stiffness, K_b, can be found by integrating the half frustum area as outlined in Equations 2.4 (integration), 2.5 (unit area of frusta), 2.6 (integration to find displacement from applied *P*), and 2.7 (individual frusta thickness). Note that *P* is the pre-tension force and *E* is Young's modulus.

$$d\delta = \frac{Pdx}{EA} \tag{2.4}$$

$$A = \pi\left(x\tan\alpha + \frac{D+d}{2}\right)\left(x\tan\alpha + \frac{D+d}{2}\right) \tag{2.5}$$

$$\delta = \frac{P}{\pi E}\int_0^t \frac{1}{\left(\tan\alpha + \frac{D+d}{2}\right)\left(x\tan\alpha + \frac{D+d}{2}\right)}\,dx \tag{2.6}$$

$$k = \frac{P}{\delta} = \frac{\pi E d\tan\alpha}{\ln\frac{(2t\tan\alpha + D - d)(D+d)}{(2t\tan\alpha + D + d)(D-d)}} \tag{2.7}$$

Since the connection is symmetric, the two stiffnesses can be added in series, and the variables from the connection can be substituted in, giving Equation 2.8 for the baseplate stiffness.

$$k_b = \frac{\pi E d\tan\alpha}{2\ln\frac{(l\tan\alpha + d_w - d)(d_w + d)}{(l\tan\alpha + d_w + d)(d_w - d)}} \tag{2.8}$$

Using Hooke's Law for springs in parallel, the stiffness constant, *C*, can then be found, as shown in Equation 2.9.

$$C = \frac{k_r}{k_r + k_b} \tag{2.9}$$

C is the proportion of the total external load that will be transferred through the bolted connection grip length. For example, in a double nut connection, if *C*=0.2, the pre-tensioned interior anchor rod grip length forces would be approximately 20% of the forces transferred from the structure to the baseplate through the standoff anchor rod distance. Note that this equation is purely theoretical and does not consider embedment of surfaces, relaxation, or performance when the anchor rods are under pre-tensioned. However, it does give a good approximation, and overview of the variables and mechanics of connection stiffness.

Looking into the mechanics of the anchor rods brings up an interesting observation. In a typical slip critical pre-tensioning application, in structural steel, a bolt acts purely as a fastener, clamping two structural members together. In SLTS structures, the anchor rods are acting as both a fastener and a structural member.

With a structural axial force based, connection, the primary fatigue loosening mechanism is from compression cycles on the bolts, which only occurs when the structural members are in compression. Tension, in a typical axial structural steel connection, will increase the preload in the anchor rod and, unless plastic yielding takes place, likely have minimal impact on a well-designed connection. With anchor rods though, both the tension and compression forces will have an impact on the loosening of the structure. Compressive forces will loosen the top nuts, while tensile forces will theoretically loosen the leveling nuts, possibly imparting increased damaging fatigue cycles on the connection.

2.7 National and International Bolt Pre-Tensioning Specifications

The review of specifications primarily focuses on standards in the US, but also covers procedures used around the world, primarily developed from European codes. Materials and hardware dimensions are only reviewed giving imperial sized connections.

2.7.1 American Association of State Highway and Transportation Officials (AASHTO)

In the US, the current prevailing specification for pre-tensioning high strength anchor rods in SLTS structures is AASHTO LRFD – SLTS 15.6.3, which states: “All anchor bolts shall be adequately tightened to prevent loosening of nuts and to reduce the susceptibility to fatigue damage. Anchor bolts in double-nut connections shall be pre-tensioned. Anchor bolts in single-nut connections shall be tightened to at least one half of the pre-tensioned condition. Anchor preload shall not be considered in design.” (AASHTO 2015). All pre-tensioning procedures are in the commentary section of the same specification and are primarily based off of Garlich and Thorkildsen (2005), with considerations from other references.

Keeping tightening practices in the commentary is likely wise of AASHTO, since specific procedures can be difficult to implement and leaves options open for individual states, which have a wide variety of SLTS bases. The AASHTO commentary tightening steps are based on a turn-of-nut procedure with a torque verification at the end and a recommended 48-hour retightening torque to account for creep in the galvanizing surface. Anchor rods are pre-tensioned to 0.5 Fy for Grade 36 rods and 0.6 Fy for 55 and 105 rods. Turn of nut is completed based on the grade and diameter of an anchor rod, as shown in Table 2.7.1.

Table 2.7.1. AASHTO top nut rotation for turn-of-nut specification

Table C15.6.3-1—Top-Nut Rotation for Turn-of-Nut Pretensioning of Double-Nut Moment Connections

Anchor Bolt	Nut Rotation beyond Snug-Tight [a,b,c]	
Diameter, in.	F1554 Grade 36	F1554 Grades 55 and 105, A449, A615, and A706 Grade 60
$\leq 1^1/_2$	$^1/_6$ turn	$^1/_3$ turn
$>1^1/_2$	$^1/_{12}$ turn	$^1/_6$ turn

[a] Nut rotation is relative to anchor bolt. The tolerance is plus 20 degrees ($^1/_{18}$ turn).
[b] Applicable only to double-nut moment connections.
[c] Use a beveled washer if the nut is not in firm contact with the base plate or if the outer face of the base plate is sloped more than 1:40.

Source: AASHTO 2015

Torque verification is completed using a derivation of the previously described processes using a nut factor, *K*, of 0.12. Additionally, AASHTO provides an option to use DTI washers conforming to ASTM F2437 for grade 55 and 105 anchor rods. AASHTO recommends that DTI washers be used on the leveling nuts to ensure proper pre-tension throughout the connection.

2.7.2 Other US Structural Connection Pre-Tensioning Standards

Besides those from AASHTO – SLTS, the American Institute of Steel Construction (AISC) and the RCSC have the leading structural bolting procedures in the US. These procedures are also adopted by the AASHTO bridge design manual for structural steel. Since most AISC and AASHTO Bridge procedures are based on those from the RCSC, the RCSC specification is primarily covered here. The RCSC specification sets a minimum required bolt pre-tension, which unlike AASHTO-SLTS, is 0.7 of the minimum bolt tensile strength. The RCSC allows for four different pre-tensioning techniques: turn-of-nut, calibrated wrench (torque), twist-off control bolts, and DTI washers. The RCSC notes that there is no method preference as long as the procedures are performed according to the specification, although turn-of-nut is indicated as more accurate. Twist-off specifications are not covered in this review since they are not applicable to foundation anchor rods.

The RCSC procedure for all pre-tension methods is inherently more accurate due to the degree of pre-tension; since bolts reach the upper inelastic portion of the stress-strain curve using the RCSC specification/procedures, the pre-tension values do not change linearly with increased turns or torques, which results in less pre-tension scatter (Fisher and Struik 1974, Bickford 1997).

The AISC and RCSC turn-of-nut specification is shown in Table 2.7.2 and is based on the bolt length and slope of the connection.

Table 2.7.2. RCSC turn-of-nut specification

Table 8.2. Nut Rotation from Snug-Tight Condition for Turn-of-Nut Pretensioning [a,b]

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 $4d_b$	⅓ turn	½ turn	⅔ turn
More than $4d_b$ but not more than $8d_b$	½ turn	⅔ turn	⅚ turn
More than $8d_b$ but not more than $12d_b$	⅔ turn	⅚ turn	1 turn

[a] Nut rotation is relative to bolt regardless of the element (nut or bolt) being turned. For all required nut rotations, the tolerance is plus 60 degrees (⅙ turn) and minus 30 degrees.

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

[c] When 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.

[d] Beveled washer not used.

Source: RCSC 2014

The snug-tight condition is defined as “firm” contact between the structural members being connected. In Table 2.7.2, the sloped connection details could likely be negated, since SLTS structure anchor rods should not be installed past 1:40 out of plumb.

For calibrated wrench (torque-based) installations, the RCSC requires that wrenches and connectors be calibrated with a bolt tension calibrator to meet the minimum pre-tensions daily under any of the following conditions:

- When the lot of any component of the fastener assembly is changed
- When the lot of any component of the fastener assembly is re-lubricated
- When significant differences are noted in the surface condition of the bolt threads, nuts, or washers
- When any major component of the wrench including lubrication, hose, and air supply are altered.

While this may seem a fairly intensive specification, for the number of bolts in structural erections and to ensure the accuracy of pre-tension, it is commonly viewed as fairly reasonable.

Finally, the RCSC allows for DTI installations according to ASTM F959. Note this is a different standard than the DTIs for anchor rods and can also include indicating, or “squirter” type, DTIs that provide correct pre-tension by ejecting a colored polymer when correctly pre-tensioned.

2.7.3 State Special Provisions

The previous project (Chen et al. 2018) covered different state practices for anchor rod pre-tensioning and found a wide variety of procedures. Some states specified torque, while others used turn-of-nut, some used DTI verification, and three left the nuts at snug-tight. For the 42 states that were found to have specifications online, 37 of them used turn-of-nut with the majority being based on AASHTO recommendations. As discussed in Chen et al. 2018, some states inspected installations after or during installations and had requirements similar to those from the RCSC.

Also from the previous project, states that specified minimum pre-tensions and had rigorous verification techniques appeared to have less of an issue with under pre-tensioned anchor rods. In addition, many of these states left the tightening method up to the contractor, requiring verification through a bolt tension calibrator. These verification techniques were often fairly draining on resources, and a couple of states conceded that the techniques are not always followed and that inspection after installation is difficult (Chen et al. 2018).

2.7.4 European Practices

European practices are generally based on EN 1090-2: Technical Requirements for the Execution of Steel Structures (CEN 2018). EN 1090-2, much like standards from the AISC and RCSC, specifies structural bolts be pre-tensioned to 0.7 of the minimum tensile strength of the bolt. Pre-tension can be induced with a torque method, a combined torque-turn method, DTIs, or twist-off fasteners. The Eurocode also uses a k class for each pre-tensioning method to designate the calibration and testing required for the installation. K0 is least rigorous with no requirement.

K1 is the next most rigorous, requiring the bolt manufacturer to provide an approximate range of nut factors for their fasteners. Finally, K2 is the most rigorous with a mean test value for the nut factor required along with the standard deviation from the manufacturer (DIN 2006). K2 also requires wrench calibration and certain fastener storage on site.

Torque control in EN 1090-2 requires K2 fasteners and is performed in three steps. The first step is snugging the installation. Second is 75% of the maximum toque. Lastly, 110% torque is applied. The 110% is to account for the immediate relaxation.

The combined method uses the first step of the torque method followed by the nut turns specified in Table 2.7.3.

Table 2.7.3. Standard Eurocode turns

Total nominal thickness "*t*" of parts to be connected (including all packs and washers) *d* = bolt diameter	Further rotation to be applied, during the second step of tightening	
	Degrees	Part turn
$t < 2d$	60	1/6
$2d \leq t < 6d$	90	1/4
$6d \leq t \leq 10d$	120	1/3
NOTE Where the surface under the bolt head or nut (allowing for taper washers, if used) is not perpendicular to the bolt axis, the required angle of rotation should be determined by testing		

Source: CEN 2018

The combined method is a K1 class. The turns are based only on the grip length and require testing for any angled installations.

2.7.5 Other Country Practices

Most other countries around the world have adopted a version of the Eurocode or RCSC specifications.

2.8 Concluding Points

- There are many accepted and proven procedures for accurate and repeatable anchor rod pre-tensioning in addition to the ones recommended in the previous study (Chen et al. 2018).
- While many states may have sufficient specifications, without proper communication and verification techniques, it is likely that they are not being implemented or that they are being ignored by contractors in the field.
- Pre-tension loss from loading can generally be negated with proper pre-tensioning force; however, there are many uncertainties with various anchor rod pre-tensioning methods.
- Relaxation and creep pre-tension loss have potentially greater impact than fatigue for MnDOT's connections.
- Error in both torque- and turn-controlled pre-tensioning can be minimized with proper procedures.
- There is an acceptable range of error in pre-tensioning between plastic yielding and approximately snug tight when there is little recorded impact on fatigue resistance.

Considering both the literature and the previous project, it is likely that successful anchor rod tightening specifications need to be effective, constructible, and verifiable. An effective specification would ensure the proper anchor rod pre-tensioning force, so that the SLTS structure will not loosen over its lifespan. Constructability is also a major key, ensuring that the specification is able to be implemented in the field. Finally, the procedures need to be verified to check on proper installation, motivate contractors to properly perform the tightening, and provide a record for asset management.

CHAPTER 3: IMPLEMENTATION OF PROCEDURES FROM PREVIOUS PROJECT

This chapter is divided into four sections: Methodology, Overhead Signs Structures, Lighting and Traffic Signal Structures, and Concluding Points. The Overhead Sign Structures and Lighting and Traffic Signal Structures sections are each split into two subsections for Installation and Maintenance procedures.

3.1 Methodology

Implementation of the specifications proposed through the previous project was designed to refine the processes in the field and ensure the constructability of both maintenance and installation procedures. All of the steps in the process followed the flowchart in the Burati et al. (2003) FHWA report.

For this project, training of technicians and iteration of the specification took place. To assist with implementation, videos, handouts, and QA/QC sheets were created referring to the new specifications. Multiple site visits were scheduled with MnDOT assistance for both overhead signs and lighting structures. The installation processes were specified to follow the new specification delivered to MnDOT through the previous project (Chen et al. 2018).

Before any maintenance on the structure, the connection is checked for inadequate clamping force by striking two opposite edges of the top and leveling washer with a pick (Figure 3.1.1).

Figure 3.1.1. Checking for clamping force in connection

If the washer moves, it indicates there is not sufficient clamping or pre-tension force in the connection. If washers were found with inadequate tension, a modified installation procedure was used as follows: Instead of snugging the nuts in two steps, nuts were taken off one at a time, lubricated with the specified grease, and turned back down to snug tight before repeating the procedure with the next nut. When following this procedure, it was important to only remove one nut at a time to ensure the structure was sufficiently clamped to the base at all times and therefore stable. After all nuts were snug tight, the normal specification procedure could be followed (Steps 6–8).

In addition to the modified maintenance procedure, instructional materials were developed to train technicians on the new specifications, following the procedure in Burati et al. (2003). Videos on the new specifications, overhead signs, and lighting structure installation were created based on installation experience and posted to the MnDOT website. The installation specification sheet for contractors was also uploaded for reference when installing new structures. Procedures for maintenance were sent to MnDOT, and maintenance personnel worked with the researchers to train on the new procedures.

For both overhead signs and lighting structures, the maintenance clamping force check with a pointed hammer has a couple of underlying inaccuracies. Control of force applied to the washer is difficult, as every worker will strike the edge of the washer with different magnitudes of force and at different angles. Also, there will be varying frictional coefficients between the washer and nut due to weathering. Finally, the washer could be pushed up against the anchor rod when striking, possibly not moving even when the connection is inadequately tensioned. Even with the inherent inaccuracies, this method presents a relatively simple and effective way of checking the clamping force in a connection.

Garlich and Thorkildsen (2005) checked for nut looseness also with a hammer, but by hitting the nuts and listening for a “dull” noise. While this method is effective for finding loose nuts, according to Garlich and Thorkildsen, it cannot differentiate between the snug-tight and pre-tensioned condition of the rod. In addition, in many older and unlubricated installations, the nuts could be rusted or corroded to the anchor rod, making it seem like the nut is still tight, but not tensioned. With both of the methods, there is significant subjectivity, but they remain a simple and fast solution to investigate whether there is any pre-tension in the anchor rod.

The notation for referring to anchor rod numbers is based on traffic direction. Facing traffic perpendicularly, numbering starts at the top left anchor rod and goes around clockwise. Figure 3.1.2 illustrates an example for a 12-rod structure.

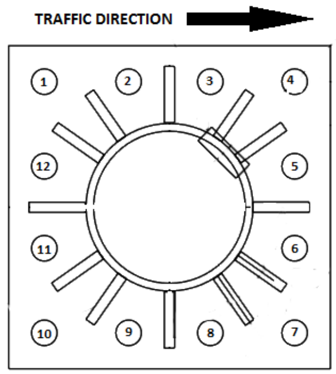


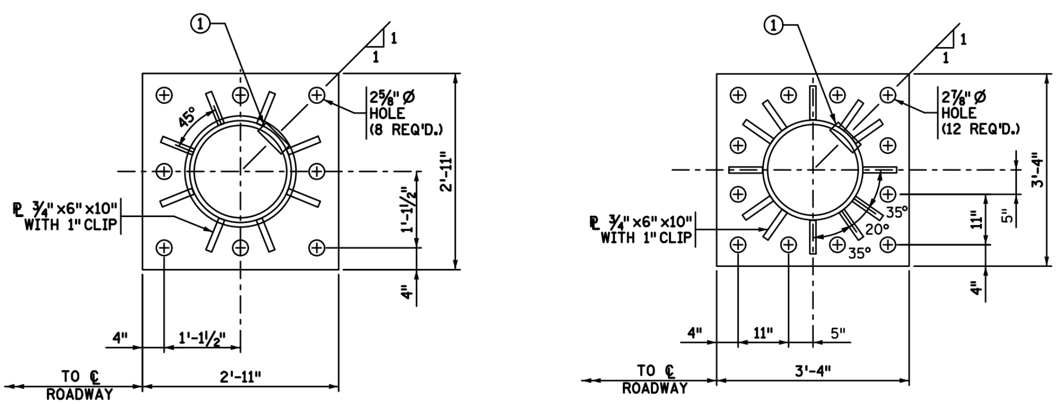
Figure 3.1.2. Example of anchor rod numbering notation on a 12-rod baseplate

3.2 Overhead Sign Structures

3.2.1 Installation

3.2.1.1 Installation Observation – 10/24/2018 and 10/25/2018

The first step of the implementation project consisted of observing the installation of two overhead sign structures on October 24 and 25, 2018. One of the structures was a cantilevered structure (OH 280-023) with a MnDOT Type B, 8-2 1/4" diameter anchor rod baseplate (Figure 3.2.1 left). The other was a sign truss (OH 94-689) with two MnDOT Type A, 12-2 1/2" diameter anchor rod baseplates (Figure 3.2.1 right).



MnDOT 2019

Figure 3.2.1. MnDOT Type B OH sign base (left) and MnDOT Type A OH sign base (right)

Grade 55 anchor rods were used in both installations. Both of the structures were installed by Global Specialty Contractors of Eagan, Minnesota. Both structures were installed at night due to traffic control requirements. Before the installation of the posts, the leveling nuts were leveled as illustrated in Figure 3.2.2.

Figure 3.2.2. Leveling nuts on sign truss structure (left) and final installation of COSS out of plumb (right)

Figure 3.2.2 (left) illustrates the leveling process on the full truss sign structure. The leveling procedure proceeded without any issues.

On OH 280-023, the cantilevered sign, more difficulties arose while leveling. The majority of the issues originated from a couple of the anchor rods that were out of plumb, but within the 1:40 limit. Figure 3.2.2 (right) illustrates that, even with the leveling efforts, the final installation on the COSS was slightly out of plumb. In addition to leveling the structure, standoff distances were also verified.

After leveling, the installation and placement of the sign structure, anchor rods, washers, and nuts could be lubricated. In the contractor's previous experience, only the anchor rods were lubricated, which would result in significantly greater friction while tightening. A copper anti-seize spray was used as the lubricant for the installation. While this was not the MnDOT-specified lubricant, spray copper anti-seize has a nut factor approximately the same as the approved lubricant, so it is likely that the pre-tension force that developed in the anchor rods was still sufficient to prevent loosening. Figure 3.2.3 (left) and (right) shows the lubricated anchor rod connection and the lubricant used, respectively.

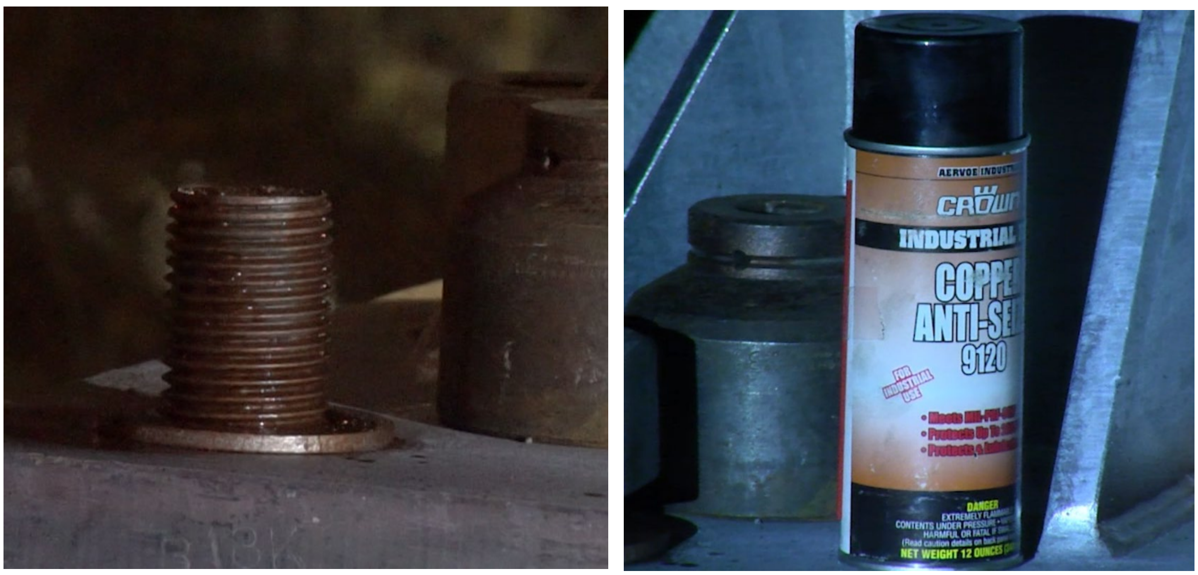


Figure 3.2.3. Lubricated anchor rod connection (left) and lubricant utilized (right)

After lubrication, the leveling nuts were approximately snugged with a pipe wrench (Figure 3.2.4 left).

Figure 3.2.4. Tightening leveling nuts with pipe wrench (left) and snugging top nuts with a calibrated wrench (right)

A pipe wrench, while not ideal, was utilized due to clearance issues; also, a large enough open-ended, calibrated wrench was not available during the installation. After snugging the bottom nuts, the top nuts were brought to snug tight in two steps using a calibrated wrench (Figure 3.2.4 right). For both steps and all following tightening steps, a star tightening pattern was utilized to ensure stresses were equally distributed in the anchor rod connections. The star pattern was new to the contractor but was followed after letting them know the significance of the step.

After snug-tightening, the contractor marked each rod and nut as reference for the turn-of-nut tightening (Figure 3.2.5 left).

Figure 3.2.5. Marking each rod and nut as reference for the turn-of-nut tightening (left) and tightening using a hydraulic wrench (right)

Anchor rods were pre-tensioned in two steps of 1/24 turn each for a full rotation of 1/12. After full application of the specified turns, the verification torque was applied to each rod. For the tightening steps, a hydraulic wrench was required due to the high torque required to achieve the turns (Figure 3.2.5 right).

After all of the steps were completed, both the contractor and inspector signed the verification form to ensure the quality of the entire new tightening process. Note that this form was signed before the 48-hour retightening torque was applied, and it was implied that the 48-hour retightening torque would be applied.

Overall, the contractors commented that the specifications were straightforward and fairly easy to follow. The only deviation from the specification was the lubrication type, and slight out-of-plumb installation of OH 280-023. For the lubrication specification, in this case, the grease is not for removals in case of a knock down like with breakaway pole bases, so if the nut factor with a different lubricant is sufficient, it is possibly acceptable to use it. Further laboratory research on the specific impact that lubrication has on the nut factor will need to be investigated.

3.2.1.2 Pre-Tension Loss Check at Various Installation Sites

Nine months after installation of both the OH sign structures, they were checked again to ensure that no nuts had come loose. Additionally, four additional OH sign structures that had been subsequently installed were also inspected. The nuts were checked with the typical procedure of striking washers with a hammer. Table 3.2.1 outlines the structures inspected, the year installed, and any notes on the inspection.

Table 3.2.1. New procedure installation inspection summary

Structure	Structure Type	Month/Year Installed	Inspection Date	Inspection Notes
OH MN 36-090	OH Cantilever	5/2019	10/2019	No Loose Nuts
OH I-94-688	OH Cantilever	10/2018	10/2019	No Loose Nuts
OH I-94-689	OH Sign Truss	10/2018	7/2019	No Loose Nuts
OH I-35-318	OH Sign Truss	4/2019	10/2019	No Loose Nuts, #5 out of plumb
OH 280-023	OH Cantilever	10/2018	7/2019	No Loose Nuts, #8 out of plumb
OH MN 51-013*	OH Cantilever	8/2017	7/2019	No Loose Nuts

*Monitoring structure was approximately installed with AASHTO turn-of-nut procedures

Of the six structures investigated in Table 3.2.1, none had loose top nuts, and the only defects found were out-of-plumb anchor rods on two of the structures. The time between installation and inspection ranged from two years to around 4 months. OH I-35-318 and OH MN 36-090 were installed in early 2019, according to MnDOT, and show that the contractors are learning and implementing the new procedures well, since they were installed without any guidance from the research team.

During July 2019, both of the OH sign structures observed in October of 2018 were inspected to ensure that no nuts had come loose with the new procedures. The full-span truss sign I-94-689 was found to have no loose nuts after checking both the top and leveling nuts. On the COSS OH 280-023, all of the nuts were tight, but, after inspection of the leveling nuts, it was found that nut 8 was slightly angled with the rod itself out of plumb (Figure 3.2.6), likely causing the issue.

Figure 3.2.6. Out-of-plumb anchor rod on COSS OH 280-023

When further investigated, it was discovered that the leveling of this particular installation took about 30 minutes and the final installation was slightly out of plumb as shown previously in Figure 3.2.2. The decreased clamping force in connection #8 of this structure may cause additional stresses in the surrounding anchor rods and could be inspected on an increased schedule as a case study.

In October 2018, three additional overhead signs that were installed with the new procedures were inspected. While more signs were installed than inspected, these three were visited given accessibility. All three of the signs had sufficient pre-tension in the anchor rods, but rod #5 on OH I-35-318 was slightly out of plumb. In Figure 3.2.7 (left), the leveling washer of rod #5 appeared to have space between it and the baseplate when compared to Figure 3.2.7 (right), which is rod #8 on the same structure. Note that the space between the washer and the nut is due to the geometry of the nut.

Figure 3.2.7. Gap between baseplate and washer #5 out of plumb (left) and bolt #8 plumb for reference (right)

When striking the washer on rod #5, it was not found to be loose, so the perceived gap may have been due to manufacturing tolerances or concavity caused by embedment.

The rest of the installations completed without observation by the research team were in good condition. As an example of an ideal structure, OH I-94-688 was installed exactly to specification, even with the turn-of-nut marks still visible on the nuts (Figure 3.2.8).

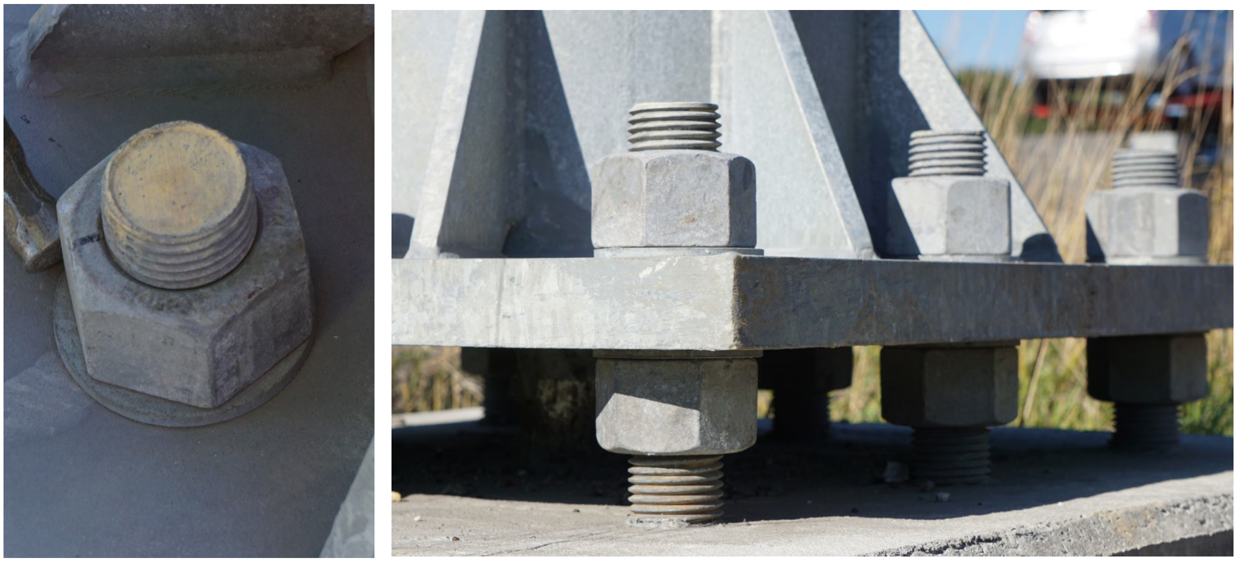


Figure 3.2.8. Turn-of-nut marks on nut (left) and baseplate of OH I-94-688 (right)

The successful installations indicate that the contractors are following the new specifications fairly well; however, knowing exact torques, lubricant, and the tightening pattern used is not possible when inspecting the structure months or years after installation.

Of all existing structures, the monitoring one, OH MN 51-013, is interesting due to the fact that it was tightened using AASHTO turn-of-nut procedures. In the first phase of this study (Chen et al. 2018), the anchor rods for this structure were pre-tensioned with 1/6 turn of nut using AASHTO procedures. This resulted in bringing the anchor rods to 70% of their yield strength, as they were mistaken as grade 105, not 55, during pre-tensioning. Although the final pre-tension is higher than expected, there has been little to no loosening of the monitoring structure. This may indicate that the pre-tension loss in connections may not be from the AASHTO procedures themselves but more so the implementation and inspection.

3.2.2 Maintenance

3.2.2.1 Existing Condition Inspections

For a comparison to the new installations and to get an approximate idea to the extent of the difficulties with maintaining existing structures, eight structures that were previously installed and maintained were inspected for looseness in the fall of 2019. Inspections were completed in the typical manner of striking the washer with a pick type hammer and observing if the washer moved.

From Table 3.2.2, it is clear that the old procedures were resulting in loose nuts on in-place structures.

Table 3.2.2. Loose nuts on inspected existing structures

Structure	Structure Type	Loose Nuts (Shaded)											
		1	2	3	4	5	6	7	8	9	10	11	12
I-94-601 EB	OH Sign Truss												
I-94-602 EB	OH Sign Truss	X	X	X					X	X	X		
I-94-608 EB	OH Sign Truss			X									
I-94-608 WB	OH Sign Truss												
I-94-606 WB	OH Sign Truss							X				X	X
I-494-153 EB	OH Sign Truss*	X		X				X	X				
I-494-199 EB	OH Cantilever												
I-494-188 EB	OH Cantilever	X	X	X	X	X							X

X=loose nuts
*Legacy design of four rod groups on two sides (8x2)

Noting markings on the structures, the I-94 structures were all retightened in 2015, and the I-494 structures were retightened in 2014. This indicates that, in the past 5 years, about half of the retightened signs re-loosened when the old maintenance procedures were followed.

The variability and weather impacts on pre-tension can also be observed through differences in the Iowa State University (ISU) inspections and the MnDOT inspections for the I-494 structures. Many of the structures that were investigated by the research team had been previously inspected by MnDOT. On many of the structures, separate inspection reports came to different conclusions regarding the anchor rods. On I-494-153, two more loose nuts were discovered compared to the MnDOT inspection. On I-494-199, the MnDOT inspection found three loose nut pairs where the ISU inspection found none. Finally, six loose nut pairs were found with the ISU inspection of I-494-188 while the MnDOT inspection found five.

Note that the MnDOT inspections indicated the number of loose anchor rods, but not the individual rods that were loose, so there could be further differences besides the number of anchor rods with significant pre-tension loss.

Discrepancies between the two inspections may be due to weather changes, further loosening of the anchor rods, or differences in striking techniques. MnDOT inspections were performed in mid-August, and the ISU inspections were performed in mid-October. Temperatures for the inspections differed by approximately 20°F, which would correspond to a theoretical temperature-induced differential stress of approximately 3.5 ksi. Temperature shrinkage may have stressed the bolts on I-494-199 enough so that the ISU inspection in the colder month of October did not observe any loose nuts, contrary to the MnDOT inspection in August of the same year.

As for the other two I-494 structures, they may have lost more pre-tension in the anchor rods, or, inherently, there may have been inaccuracies with the pre-tension checking method.

Since the washers are struck with a hammer to check pre-tension, the results are somewhat subjective and dependent on speed of the strike and washer position on the structure. One inspector may strike the washers with more force than another. Additionally, if a washer is hitting the anchor rod, it will not move as much when struck, possibly resulting in a false recording.

The results in Table 3.2.2 may also indicate that nuts come loose in groups. Although the sample size is small, most of the observed loose nuts are next to each other. This behavior would make sense, as when one nut comes loose, more stress is put on the surrounding ones. Observations in numerical models from Phase I also support the theory that the anchor rod nuts come loose in groups. If the connections are put into compression, this may shake the nut loose and be amplified as more nuts get loosened.

Conditions were also noted during inspections of the existing signs. For most, the installations were fairly new and in good condition. The I-494-153 sign truss structure was in slightly worse condition than the other observed structures and is an older design as indicated by the 8x2 rod layout pattern. Figure 3.2.9 shows the standoff distance issues that were found during inspection.

Figure 3.2.9. Large standoff distance on I-494-153 structure

On this structure, the standoff distance was about twice the specification of the one-bolt diameter. Both Dexter and Ricker 2002 (NCHRP) and Hosch (2015) found that increased standoff distance significantly increases the fatigue loading on the anchor bolts. In addition to the fatigue from the standoff distance, Dexter and Ricker found that having connections under sung tight increases fatigue loading on bolts due to wedging of the baseplate. With these two factors coupled, the anchor rods on this structure were likely undergoing far greater fatigue loading than a comparable, correctly installed structure.

3.2.2.2 Maintenance Observations

On July 11, 2019, modified maintenance procedures were implemented on existing MnDOT full-span overhead structures. Overall, five structures were tightened, with two using the new specifications and the other two tightened to 3,650 ft-lbs of torque (due to no rods being loose). Due to traffic control concerns and the structures already being installed, the inspection and maintenance procedures were modified to the following sequence:

1. Check both top and leveling washers for looseness by striking with a hammer on two sides.
2. Take off nuts individually, lubricate, and bring to snug tight in a single star pattern. Ensure that only one nut at a time is removed, lubricated, and snugged.
3. Bring to 50% verification torque (*Tv*) in a star pattern.
4. Bring to 110% *Tv* in a star pattern.

Snug tight had to be completed in one step, one nut at a time, to ensure the structure was effectively anchored to the base. Removing all of the anchor rod nuts at once could result in collapse of the structure, so it was critical that this step was performed one nut at a time.

Turn of nut was not utilized at the request of MnDOT personnel due to uncertainties about the existing conditions and to avoid yielding the anchor rods. Reference turn-of-nut marks were used for verification of torque and to understand approximate torque-turn relationships in maintenance conditions.

The rods were immediately brought to 110% *Tv* in two star patterns. This was done due to feedback that it was unrealistic to come back 48 hours after tightening and would put a significant drain on resources, especially for difficult-to-reach locations that require traffic control. In addition, several sources (Fisher and Struik 1974, Bickford 1997, James et al. 1997, Phares et al. 2016) indicate that the immediate 110% will result in less final uncertainty than other tightening factors such as varying nut factors, tool error, torque-controlled pre-tensioning, and differential tightening.

Maintenance notes for each structure following their inspection processes throughout the day (July 11, 2019) follow. The increasing or decreasing notation refers to the side of the highway that the structures were on. Increasing indicates that traffic is traveling toward the structure, while decreasing indicates that traffic is traveling away from the structure.

I-94-601 (Increasing Side) – Figure 3.2.10

Figure 3.2.10. I-94-601 Base

Inspection and maintenance on this structure went from 7:20 a.m. to 8:05 a.m. All of the nuts were checked for looseness, with none found to be loose. Because none of the nuts were loose, all were torqued in a single star pattern to 110% Tv. Nut 3 was the only one that turned slightly. It was also found that the gauge on the pump was zeroed at 300 psi, so all pressures had 300 psi added to them. The maintenance procedure was not used on this sign because all nuts were tight, and it was desired to establish a baseline for the new specifications for future inspections to compare the procedures performed.

I-94-602 (INCREASING SIDE) – FIGURE 3.2.11

Inspection and maintenance for this structure took longer than the first, due to the new procedure being used. While striking the washers, concerns were voiced by MnDOT maintenance personnel about whether a washer was pushed up against the rod, so it would likely be beneficial to strike opposite sides of the washer when checking for looseness, as demonstrated in Figure 3.2.11 (right).

Figure 3.2.11. Full truss OH sign I-94-602 (left) and inspecting rod pre-tension force (right)

After inspection, nuts 1, 2, 3, 8, 9, and 10 were found to be loose, so the new procedure was used for retightening. While taking off the nuts, it was discovered that many were rusty or corroded on the interior of the threads. The condition of the threads was likely due to chlorides from deicing salt infiltrating through small gaps, but was somewhat unexpected considering that the threads are completely covered by the nuts and washers. Rod 10 was found to be out of plumb (Figure 3.2.12), which led to a much higher turn-of-nut value than expected that possibly did not develop the full tension in the rod.

Figure 3.2.12. Rod 10 out of plumb and misaligned

I-94-608 (Increasing Side) – Figure 3.2.13

Only one rod, #3, was found to be loose, but the procedure was still followed to take all of the nuts off and lubricate to reset the installation. Much like the previous structure, rod threads were fairly corroded on the inside of the nut (Figure 3.2.13 left).

Figure 3.2.13. General condition of anchor rods (left) and sample turn-of-nut verification (right)

Turn of nut was also measured to compare the specified torque to the “required” turn-of-nut values (Figure 3.2.13 right).

During this inspection, it was found that snugging the nuts with a torque wrench significantly increased the efficiency of the process, because it removed the need to switch the reaction arm of the hydraulic wrench for every rod, as required during initial snugging. The increased efficiency led to this inspection and maintenance taking half an hour less than the first structure. In addition, lubricating the top threads of the rod before loosening lowered the torque demand; before this, many nuts would take greater than 110% *Tv* to remove due to friction in the threads.

I-94-608 (Decreasing Side) – Figure 3.2.14

On this structure none of the washers moved when struck, so it served as another control variable where all of the nuts were brought to 110% *Tv* in a star pattern. In Figure 3.2.14 (left), the post has a tag marking the designation and a C-15 marking painted on.

Figure 3.2.14. I-94-608 Post (left) and 1/12 turn on nut #8 (#2 in star pattern) (right)

The C-15 marking indicates that the structure was retightened in 2015. Before tightening, all of the nuts were marked where they started so turn measurements could be taken. Overall, three nuts turned: 8, 10, and 11. Of these three, nut 8 turned the most at about 1/12 of a rotation, shown in Figure 3.2.14 (right). The 1/12 turn on rod 3 may indicate that it was approximately sung tight, since 1/12 is the specified turn for full pre-stressing. Due to lubrication conditions though, there is a greater likelihood that the leveling nuts for the nuts that turned were not snugged up against the baseplate and that the turns were more a result of straining the entire anchor rod to "pull" the leveling nut snug to the baseplate.

I-94-606 (Decreasing Side) – Figure 3.2.15

On this structure, nuts 7, 11, and 12 were found to be loose and rod 8 was missing a top washer (Figure 3.2.15 left).

Figure 3.2.15. Missing washer on rod 8 (left) and excessive turn of nut on rod 11 (right)

For the procedure on this base, nuts were immediately brought from snug tight to 110% *Tv* in a star pattern to investigate if the half step could be eliminated for efficiency. For this structure, skipping the half step enabled the procedure to be completed 15–20 minutes faster than it took on the previous processes. However, future inspections will need to document if skipping this step negatively impacts the fatigue resistance of the pre-tensioned connections. On the east side of the structure, many of the nut turns were far greater than expected, at about three times the specified amount. As shown in Figure 3.2.15 (right), nut 11 turned 3/12 from snug, a full 300% of the AASHTO specification.

OVERHEAD SIGN MAINTENANCE SUMMARY

Table 3.2.3 shows the turn-of-nut value achieved at final torque.

Table 3.2.3. Final turn-of-nut values and Inspection and maintenance time

Structure	Final Nut Turns												Time (min)
	1	2	3	4	5	6	7	8	9	10	11	12	
I-94-601 EB*	0	0	1/24	0	0	0	0	0	0	0	0	0	45
I-94-602 EB	3/24	3/12	x	1/6	3/24	1/12	1/12	1/12	1/6	3/12	x	1/6	120
I-94-608 EB	1/12	1/24	1/12	1/12	1/6	1/6	3/24	1/12	1/6	x	1/12	1/12	90
I-94-608 WB*	0	0	0	0	0	0	0	1/12	0	1/24	1/24	0	25
I-94-606 WB	3/12	1/12	1/12	x	1/12	3/24	1/6	3/24	1/6	1/12	3/12	3/12	70

*No washers moved during inspection, so full re-tightening maintenance procedure was not used

Note that for I-94-601 EB and I-94-608 WB, the retightening procedure was not used, so the values are for reference only. The boxes are shaded according to how far off from the specified turn of 1/12 they were. The farthest observed, 3/12, is red, with closer values approaching green at the specified 1/12 of a turn. Boxes with an x indicate that the turn was not recorded for that nut.

It is likely that the new procedure will add about 30 to 60 minutes to the maintenance of each structure. From the results in Table 3.2.3, the inspection and maintenance times decreased as the day progressed for respective procedures. With the control procedure of only tightening, the procedure was completed 20 minutes faster, likely due to a learning process concerning the steps and tooling. With the new procedures, inspection and maintenance time was improved by approximately 30 minutes after each experience. The improvement was attributed to learning and finding quicker procedures as the day progressed.

Maintenance times were completed with a three-person crew. The procedure could likely be done with two people to cut down on labor and vehicles required on site, but may increase the duration of time to complete maintenance. Additionally, it is unlikely that the new procedures will take less than 60 minutes to complete when traffic control, travel, and other considerations are averaged out for all structures.

Turn of nut may not be reliable for existing maintenance/correlate well with torque. Table 3.2.3 shows that of the structures that the procedure was used on, and 40% achieved the specified turn-of-nut value. Since the connections were pre-tensioned to 110% of the required torque, it is possible that the turn values could be higher, but even when considering the 3/24 turns, only 56% of the nuts reached the specification. 15% of the nuts turned triple the AASHTO required value. From calculations, the 300% turn would indicate yielding of the rod; however, considering the torque value used, it is unlikely that the rods yielded, especially with the less-than-ideal lubrication conditions.

Many factors could play into the excessive turn-of-nut values. One major factor could be the tightness or level of the leveling nuts. If the leveling nuts are slightly loose, or lower than the surrounding nuts, the grip distance would be increased to where the rod is fixed in the concrete. This condition strains the entire anchor rod until the leveling nut is pulled up to the baseplate during pre-tensioning. Another reason for the increased turns could be that the galvanizing finish on the existing washers or anchor rods is slightly deforming. Finally, the rods may not be completely level, which increases the grip distance and results in stress concentrations in the connection.

Due to many existing unknown factors, it is likely that taking the nuts off, lubricating, and using torque will provide greater accuracy in final tensions when compared to turn of nut. In addition, the torque spec would likely prevent under tightening since only one nut out of all in the new procedure turned under 1/12.

Lubrication and taking off nuts is critical to “reset” the installation. If only torque is used for maintenance, it is critical that each nut is taken off, lubricated, and replaced at snug tight. As observed, every nut that was removed had rust and corrosion within the threads, even though no interior threads were exposed to the elements. To remove loose nuts (i.e., ones without pre-tension left in the connection), sometimes 100–150% of the tightening torque was required due to friction, indicating the impact that friction has on an installation. Without cleaning and re-lubrication, there is no way to effectively know the existing conditions and friction in the connection, so any sort of tightening, be it turn-of-nut or torque, is effectively guesswork.

3.3 Lighting and Traffic Signal Structures

3.3.1 Installation

3.3.1.1 Light Pole Installation Observation

On October 29, 2019, researchers visited the installation of a 9-40 ft stainless steel light pole on a construction project in Mendota Heights, Minnesota, located in the northeast quadrant of the TH 110 and TH 35E east junction. The pole base had a 15" bolt circle and was set on a MnDOT Design E concrete foundation consisting of four Type B, Grade 55, 1" diameter anchor rods in accordance with MnDOT Specification 3385.

The installation process followed the new procedures. First, the installation was verified, ensuring that the correct anchor rods, nuts, and washers were being used for the project. The rods, nuts, and washers on this particular project were checked to be Type B, Grade 55, 1" diameter anchor rods in accordance with MnDOT Specification 3385. The specific requirements included the following:

- Four 1" diameter anchor rods, projecting at least 3 5/8" and no more than 4" from the top of the foundation
- Eight 1" diameter nuts
- Eight standard ASTM F436 washers
- Four ½" thick washers (no longer required by the pole manufacturer)

The contractor lubricated the bearing surfaces of the leveling nuts and washers and the threads of the anchor rods. As the leveling nuts were turned down onto the anchor rods, the inside threads of the nuts were also lubricated, as shown in Figure 3.3.1 (left).

Figure 3.3.1. Placing leveling nuts (left) and verifying standoff distance (right)

After the leveling nuts were turned down onto the anchor rods, the contractor adjusted each leveling nut to the required standoff distance (Figure 3.3.1 right). The standoff distance is either specified by the manufacturer or the MnDOT typical standoff distance of less than one anchor rod diameter.

The contractor used a level to level the leveling nuts (Figure 3.3.2 left).

Figure 3.3.2. Leveling process (left) and improper lubrication of leveling nuts (right)

Once leveled, the contractor lubricated the top and bottom surfaces of the ½" thick washers and placed them on top of the leveling nuts (Figure 3.3.2 right). Note that lubrication of the washers on the nonbearing surfaces is a deviation from the specification requiring lubrication of bearing surface nuts and washers. This may result in less clamping friction between the double nut moment connection and the baseplate. Additionally, the lubricant used was a deviation from the specification, using a brush-on copper anti-seize, instead of the MnDOT-specified Bridge Grease.

The light pole was then lifted via crane and guided onto foundation anchor rods. Washers were placed on top of the pole baseplate. The bearing surfaces of the washers and top nuts were lubricated, and the top nuts were turned down by hand onto the anchor rods making contact with the washers.

Next, two cycles of snug tightening were completed in a star pattern sequence. The top nuts were tightened to the snug-tight condition first, followed by the snug-tight condition of the leveling nuts. The contractor had the option of using either a 12" long offset wrench made by the pole manufacturer, a 12" long open-end and closed-end wrench, or a torque wrench set to 50 ft-lbs. For the first cycle, the contractor utilized the manufacturer's 12" long offset wrench to bring the leveling and top nuts to a snug-tight condition, as shown in Figure 3.3.3.

Figure 3.3.3. Snugging top nuts (left) and snugging leveling nuts (right)

The top nuts were then marked to visualize the turn of nut needed. The new specifications required 1/18 of a turn for proper pre-tension in these anchor rods. According to the proposed tightening specification, this step should be performed over two 1/36 turn steps.

The turn of nut was accomplished using the closed-end wrench on the top nuts. The contractor found it difficult to achieve these turns, not due to tension from turning the nuts, but rather because of lack of space inside the pole base to use the closed-end wrench and not being able to see the required 1/18th turn marks inside the pole base.

Figure 3.3.4 (left to right) shows examples of one nut before, at a second step, and after the contractor completed turn-of-nut pre-tensioning, respectively.

Figure 3.3.4. Nut turns at initial, second step, and final values (left to right)

The limited clearances are fairly apparent in Figure 3.3.4 with almost no turn visual from the initial to second step. Also note the fine sand particles in Figure 3.3.4 (right). To prevent contamination of the anti-seize lubricant on anchor rod and nut threads and the bearing surfaces of nuts and washers, debris inside poles should likely be removed before installation.

The last step, shown in Figure 3.3.5, required the contractor to use a torque wrench set to 200 ft-lbs.

Figure 3.3.5. Applying verification torque

The contractor applied the torque wrench to the top nuts, tightening in two cycles. Lastly, the contractor is required to apply a re-tightening torque to the top nuts 48 hours after installation. The contractor can use the same torque wrench, this time set to 110% of the verification torque, 220 ft-lbs. The contractor should apply the re-tightening torque in two cycles.

In speaking with the contractor, it seemed as though there were three main areas of the new tightening procedure that differed the most from old tightening specifications, as follows:

- Areas of lubrication on nuts and washers differed from past procedures. Much like during the installation of the overhead sign, the contractor was only used to lubricating the threads of the anchor rod. While this would ensure that the inside faying surfaces of the nuts were lubricated, critical surfaces would be left unlubricated (top surface of the leveling nut, bottom and top surfaces of the washers, and bottom of the top nut). In addition, unneeded surfaces like the leveling nut washers were lubricated, which could decrease friction in the baseplate connection, requiring less shear force to induce a slip condition to the double nut connections.
- In past tightening methods, the contractor tightened the bottom nut using the turn-of-nut required, rather than the top nut. Additionally, a verification torque was not applied after the turn of nut.
- The contractor completed only one round of tightening for snug and turn-of-nut tightening, rather than two rounds.

Overall, the tightening of anchor rods in light pole structures revealed serious constructability issues. Unlike overhead signs, the nuts are in very tight spaces, and effectively tightening them can be difficult with certain equipment. Additionally, accurate turn-of-nut measurement is difficult within the base, especially with conduit and wiring also installed.

3.3.1.2 Light Pole Installation Procedure Test

For 50' tall light poles, with 1 ¼" diameter, Grade 55, anchor rods, the recommended specifications called for 400 ft-lbs of torque and nearly 600 ft-lbs for steel screw-in type foundations. After the field experience, concerns were raised about clearances and the capability of achieving higher torque inside the limited base space. This installation was primarily for demonstration purposes for torque, so angle measurements were not recorded.

On December 20, 2019, the pole manufacturer, Millerbernd Manufacturing Company of Winsted, Minnesota, hosted a schematic demonstration with River City Electric of River Falls, Wisconsin. The demonstration was to show that the required pre-tensioning torque could be achieved within the base constraints and to practice the tightening specifications.

The Grade 55 anchor rods were welded onto a steel plate for demonstration purposes. The initial installation was done correctly, without lubrication on the top of the leveling nut washers, as shown in Figure 3.3.6 (left).

Figure 3.3.6. Correctly installed leveling nuts and washers (left) and leveling installation (right)

Figure 3.3.6 (right) illustrates correct leveling procedures performed on the installation. After leveling, the base was placed, and all required surfaces were lubricated with the specified grease, as shown in Figure 3.3.7 (left).

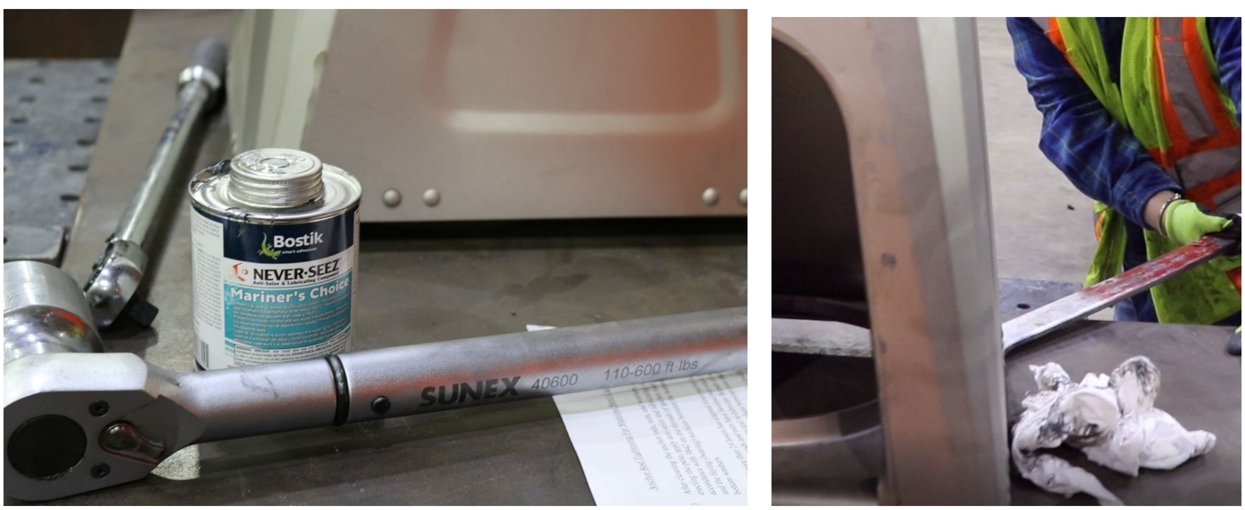


Figure 3.3.7. Calibrated torque wrenches and specified grease (left) and snug tightening leveling nuts (right)

Top nuts were then brought to snug tight using 50 ft-lbs of torque applied with the calibrated wrench shown in the background of Figure 3.3.7 (left); the calibrated torque wrench in the foreground was used for the second and final torque. The leveling nuts were snugged with an open-ended wrench, as shown in Figure 3.3.7 (right), which works well for the process, but was held past the 12" specified snugging distance for 1 ¼" diameter anchor rods. In addition, the star pattern was not followed, so some differential stresses may have been induced.

Finally, the anchor rods were immediately stressed to the full 400 ft-lbs in one step with a calibrated torque wrench (Figure 3.3.8).

Figure 3.3.8. Final verification torque on the structure installation

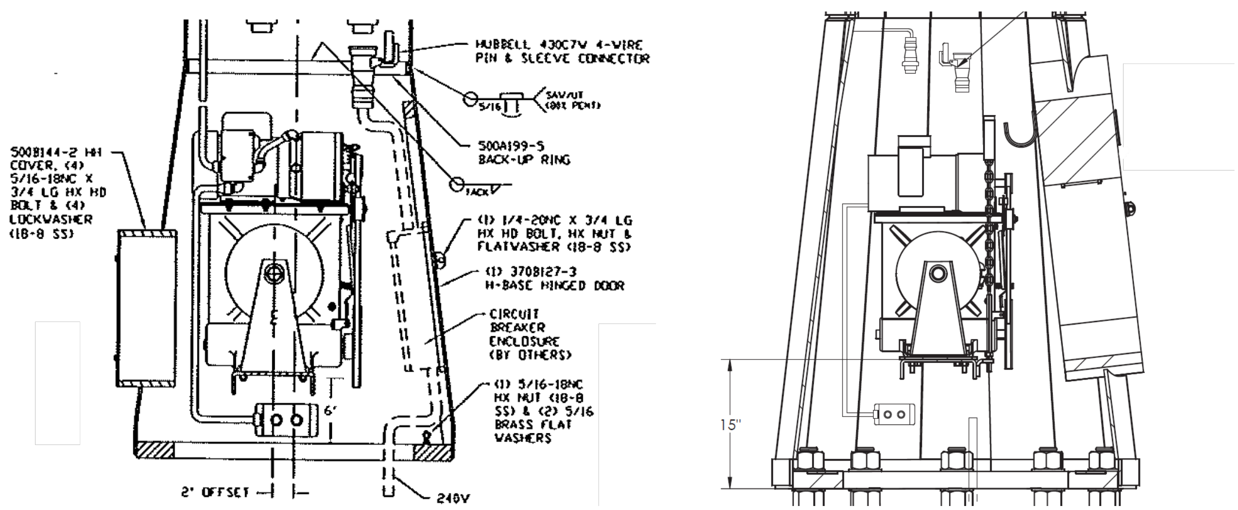
The contractor then reapplied the verification torque as the last step. This deviation from the specification indicates that the procedures should likely have a half-torque step, or better clarify the two steps. The star pattern was applied per the new procedures.

Overall, the contractor found the specifications fairly easy to follow and recommended that the steps be separated individually, instead of two steps for each specified torque or turn. In addition, the torque-controlled pre-tensioning was far preferred over turn-of-nut due to the limited visibility in light pole bases (personal interview with Mark Draper, foreman for River City Electric, December 20, 2019).

3.3.1.3 High Mast Light Tower Installation

Over the time period that the study was taking place, an HMLT installation using a hydraulic torque wrench was not able to be observed. HMLTs are fairly specialized lighting structures, and new installations are not routine. Although no installations with the low-profile hydraulic torque wrench were directly observed, the clearances were modeled using computer-aided design and drafting (CADD), and conclusions were drawn based on field experiences.

For a general overview of HMLT bases, Figure 3.3.9 illustrates the interior view of the MnDOT legacy HMLT base design and the new HMLT base design.



Millerbernd 2019

Figure 3.3.9. Legacy HMLT base design (left) and revised current HMLT base design (right)

Note that the interior anchor rod design is preferred by MnDOT for increased fatigue performance and to protect anchor rods from the elements. The winch assembly in the base is utilized for raising and lowering the luminaries at the top of structure during maintenance. Between the legacy and current designs, the major changes to improve clearance were raising the winch assembly up 9", making the maintenance openings larger, and increasing the distance of the wall to the anchor rods. While these were not the only changes made, they were the ones that improved the accessibility the most.

Additionally, when comparing the two drawings, the clearance improvements of the updated design are fairly clear. While pre-tensioning of the anchor rods can be completed from the leveling nuts, this operation is not desired if possible. Any turning of the leveling nuts can bring the installation out of plumb. Also, an open-ended wrench is required for tensioning the leveling nuts. Due to the relatively significant torque required for the proper pre-tension, open-ended wrenches run into clearance issues between the foundation and baseplate of HMLTs due to their required thicknesses.

On the single observed HMLT installation, the tower anchor rods were pre-tensioned to snug tight with a calibrated manual wrench. It was intended that the HMLT anchor rods would be fully pre-tensioned at a later date using a hydraulic torque wrench. The manual wrench worked fairly well in the updated base, especially with the raised winch detail. As shown in Figure 3.3.10, clearance was limited when torqueing the nuts closest to the door and required a fairly fine-toothed socket wrench to tighten.

Figure 3.3.10. Manual wrench installation tightening of HMLT anchor rods

The manual wrench worked sufficiently for bringing the nuts to snug tight; however, it cannot generate enough force to reach the required torque necessary to properly pre-tension HMLT anchor rods. Clearances for the hydraulic wrench were schematically investigated using CADD.

The limiting clearance area for the hydraulic torque wrench was due to the sloped inner sidewall of the HMLT base. In both the existing new and old base designs, this proved to be an issue. Primarily, the clearance problems were observed on nuts that were next to each other, likely indicating that the tolerances in the baseplate holes contributed to the inability to place the hydraulic wrench, moving some nuts closer to the tower wall and others farther away. Working with the manufacturer, the base clearances were increased by an inch to help with installation, which is greater than any of the clearance issues experienced in the field. It is likely that the low-clearance hydraulic wrench will work in the redesigned bases.

3.3.2 Maintenance

Maintenance work on lighting and traffic signal structures focused on traffic signal poles and HMLT structures due to the limiting clearances and high torque required for proper pre-tensioning. Most of the effort was put toward finding a feasible maintenance option for the existing HMLTs since clearances inside the legacy bases is a limiting factor for pre-stressing.

3.3.2.1 Traffic Signal Mast Arm Pole

The maintenance procedures were investigated on a Type PA traffic signal pole installation. The signal mast arm pole that was retightened is located at the northeast corner of the T-section of County Road 14 (34th Street North and Century Avenue North in Oakdale, Minnesota) and MN 120. This pole was the only one retightened as a proof of concept for clearance. Preliminary CADD drawings (Figure 3.3.11) indicated sufficient clearance, but the condition needed to be further investigated in the field.

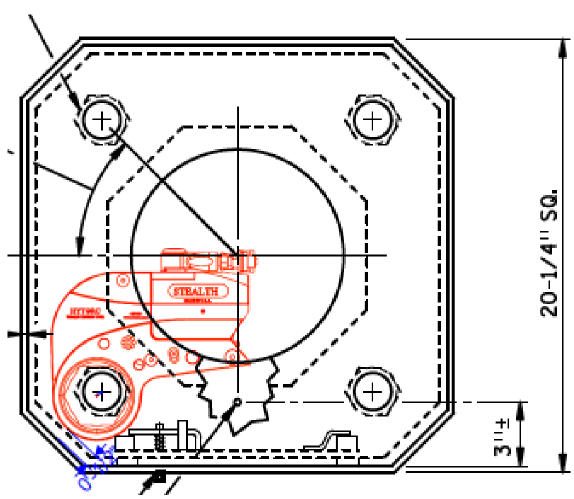


Figure 3.3.11. CADD modeled hydraulic wrench clearances

Much like the OH sign structures, the installation procedure was modified for maintenance operations. The major difference between the OH sign and traffic signal mast pole maintenance was that the nuts were immediately brought to the 100% verification torque without a half step. The procedure was modified because the limited clearances make it difficult and far slower to maneuver the wrench around in the base. The maintenance procedure is as follows:

1. Take off the nuts, lubricate, and bring to snug tight in a single star pattern.
2. Bring the nuts to 100% verification torque in star pattern.

When checking the looseness of the nuts by striking with a hammer, it was discovered that clearance issues did not allow for accurate measurement of the clamping force in the connection. In lieu of striking with a hammer, the approximate torque required to loosen all nuts was measured. Starting with the first nut, the wrench was set at 1,500 ft-lbs and easily loosened the nut, and the next three nuts came loose at about 800 ft-lbs, which indicates that all of the connections were likely torqued to no more than 800 ft-lbs during initial installation. After loosening the nuts, it was found that the anchor rods were lubricated with what appeared to be the specified grease (Figure 3.3.12 left).

Figure 3.3.12. Previously lubricated anchor rod (left) and clearance with ground lug (right)

The installation was fairly new (circa 2015), so not much weathering had taken place. After removal, each nut was lubricated and brought to snug tight. The final snug tight was slightly higher than the specification due to the minimum torque on the wrench, but for pure torque installation, the initial snug value does not impact the final pre-tensions greatly.

Turn of nut for this installation was not utilized due to the small clearances. One issue found while retightening the nuts was that the ground wire connection prevented the wrench from being placed on the baseplate of the structure for the front nuts, as shown in Figure 3.3.12 (right).

The wrench was still able to tighten the nuts, but care was needed to prevent wedging or pinching when using the wrench placed on top of the ground wire. The ground connection could also be loosened to help with clearance (3.3.13 right).

Figure 3.3.13. Galvinizing dimples on washer (left) and moved grounding wire (right)

It is also important for safety that the fuses for the signals are pulled before maintenance. Finally, Figure 3.3.12 (left) details dimples in the galvanized surface of the washers. These could possibly add to relaxation losses and deform during tightening.

3.3.2.2 HMLT Tightening Procedures

Existing HMLT structures presented the limiting situation for effective anchor rod pre-tensioning. Hydraulic torque wrenches are required for turning the top nuts when tightening anchor rods on HMLTs because of the high torque values necessary to tension Grade 105 anchor rods. Manual wrenches cannot meet the required torque values to properly tighten the anchor rods. A bolt jacking solution was not chosen due to clearances inside the base design and the fact that jacking the entire structure up would be difficult. The same clearance issues limited the use of gear drive wrenches.

Three different methods were attempted for re-pre-tensioning existing HMLT bases: HYTORC hydraulic wrench, Millerbernd designed J Wrench, and a slug wrench.

HYTORC Stealth 4 Hydraulic Torque Wrench Assessment

July through December 2019, the HYTORC low profile Stealth 4 hydraulic torque wrench with a HYTORC Vector hydraulic pump was assessed for maintaining anchor rod connections on existing structures. The maintenance sequence was modified from the original tightening specifications intended for new installations, as follows:

1. Take off the nuts one at a time, lubricate threads of nuts and anchors and the bearing surfaces of nuts and washers, install F436 washers where washers were not originally used, and bring to snug torque in a single star tightening pattern. Ensure that only one nut at a time is removed, lubricated, and snugged.
2. Bring to 100% T_v in a star tightening pattern.

Due to all nuts being snug torqued during the initial stage, it is recommended not to perform this procedure on windy days.

In regards to the changes, snug torque was completed in one step to ensure the structure was effectively anchored to the base. The turn-of-nut step was not utilized due to uncertainties about the existing conditions, to avoid yielding the anchor rods, and because of limited accessibility. Final tightening for the anchor rods were immediately brought to 100% *Tv*.

HMLT S09A 2 – HYTORC Wrench

This HMLT located on I-494 near the Wakota Bridge crossing over the Mississippi river is a legacy design structure shown in Figure 3.3.14 (left).

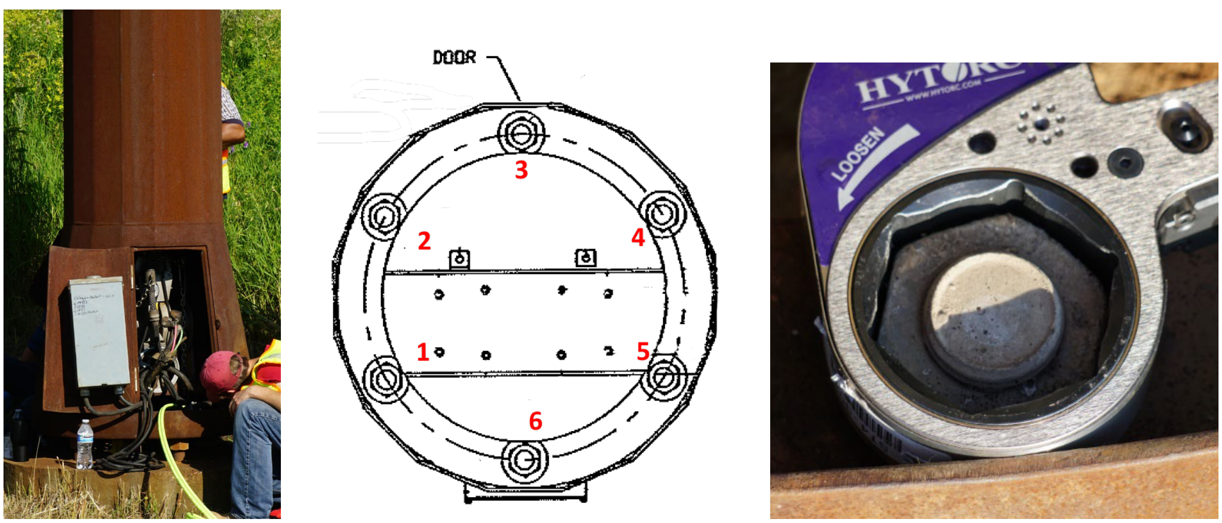


Figure 3.3.14. S09A 2 legacy base design (left), anchor rod numbering (center), and wrench clearance issues (right)

Figure 3.3.14 (center) shows assigned numbering of the anchor rods. For removal and retightening, the hydraulic torque wrench could only be placed on nuts 4 and 6. The wrench would likely fit onto the top nuts once in place; however, the lack of sufficient clearance between the taper of the sidewall and the top nuts make it infeasible for the wrench to get past the taper and onto the top nuts. Figure 3.3.14 (right) shows that the wrench fits on the nut, but would have to be forced past the taper of the sidewall and would be fairly difficult to remove.

The taper of the structure wall was found to be the primary clearance issue as outlined in Figure 3.3.15 (left).

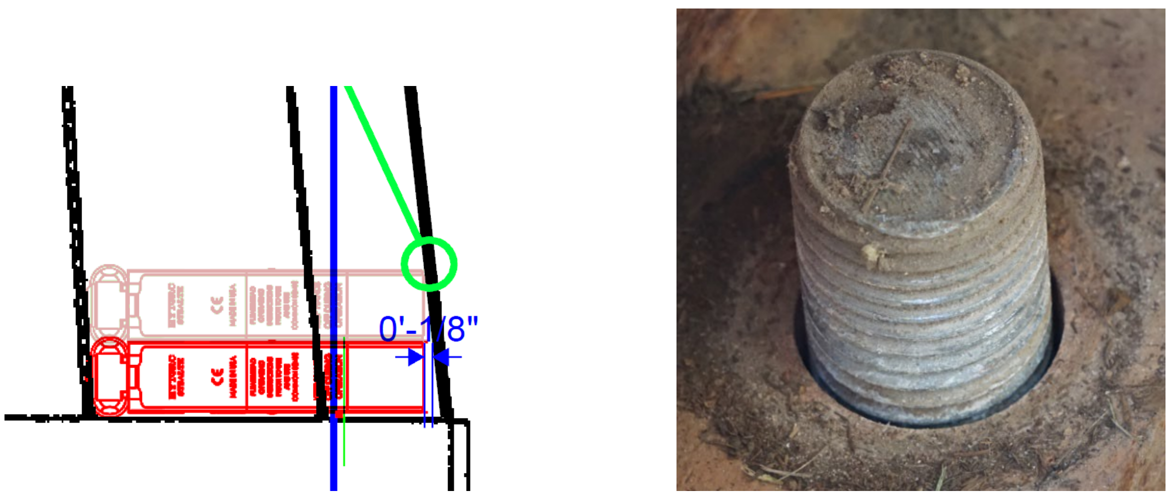


Figure 3.3.15. Wrench clearance issues (left) and anchor rod condition (right)

This limiting taper was improved in the current HMLT base designs. On the two top nuts that were taken off, galvanization was in fair condition with minimal rust or corrosion (Figure 3.3.15 right). Since this HMLT is not directly next to the road, the structure is exposed to less chloride exposure from chemicals used in snow and ice removal, unlike many OH sign structures. In addition, the top nuts are enclosed in the HMLT base and consequently not fully exposed to the elements and corrosive chemicals.

HMLT A14E 4 – HYTORC Wrench

This HMLT is located at the I-94 and I-494 interchange near Maple Grove, Minnesota. The structure has a newer eight-rod pattern and a larger base design than the legacy HMLT base at the Wakota Bridge. Note that this HMLT base design has slightly smaller clearances than the current design previously outlined in Figure 3.3.9.

This base was an intermediate design between the legacy base and the current design partially due to the findings of this project. In the intermediate base design, the hydraulic wrench experienced wedging against the sidewalls due to the sidewall taper, although to a lesser degree. Compared to the legacy design, a greater number of top nuts on this newer HMLT base design were accessible for re-tensioning. Referencing Figure 3.3.16 (left), only nuts 6 and 7 were not able to be retightened.

Figure 3.3.16. Rod numbering (left), checking washers for looseness (center), and prior copper anti seize lubrication on rod (right)

Before loosening, the leveling nuts were checked for tightness (Figure 3.3.16 center) and none were found to be loose. Because the striking had to be completed on the leveling nuts, this may not be an ideal indicator of clamping force.

The new procedure was attempted on the structure to investigate the feasibility of the new design even though no nuts appeared to be loose. While loosening the nuts, lubricant from the initial installation was present (Figure 3.3.16 right).

Because the nuts were lubricated during the initial installation, a tightening torque value could be approximated based on the loosening torque. All of the top nuts came loose at about 1,000 ft-lbs of torque. It's likely that the bottom nuts were torqued to a maximum of 1,500 ft-lbs. This torque value would match up with the DOT's observations of the contractor using a 10' long breaker bar over the handle of a pipe wrench to turn the bottom nuts tight. While the original installation likely used far less than the required torque value, it does show that the clamping force can be transferred relatively well by only tensioning the leveling nuts.

HMLT TW06A 1 - HYTORC Wrench Stack Socket Attachment

To alleviate clearance issues, the hydraulic torque wrench manufacturer recommended a socket attachment fitted to the wrench. Although the socket raises the wrench higher into the taper of the HMLT, it also allows for a smaller diameter wrench head to be used on the top nuts, therefore positioning the wrench farther away from the taper. Figure 3.3.17 illustrates the hydraulic torque wrench with the stack socket attached.

Figure 3.3.17. HYTORC Stealth 4 hydraulic wrench with stack socket

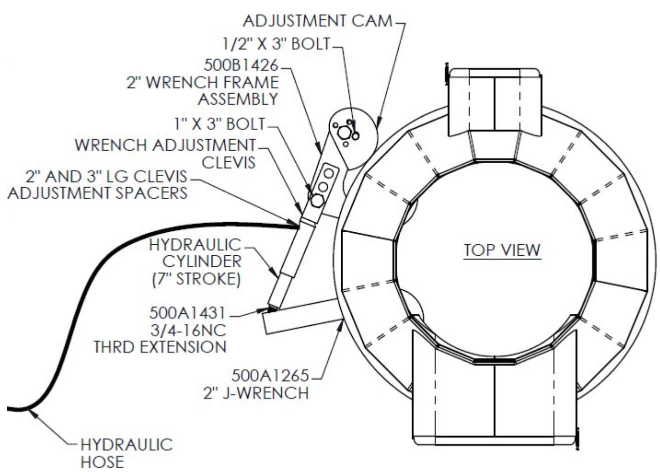
Note that the piston and hoses that power the wrench are unattached. Clearances with the stack socket are improved from using the wrench alone, but there were still a couple wedging issues, especially when the anchor rod protrusions extended beyond the top nuts, lifting the stack socket up into the base sidewall, as shown in Figure 3.3.18 (right).

Figure 3.3.18. Wedging on door frame (left) and socket raised into wall by nut protrusion (right)

Note that unlike many socket wrenches, the stack socket partially covers the nut, as shown in Figure 3.3.17 (left). As shown in Figure 3.3.18 (left), the stack socket does not work on the top nuts that are centered at the access door openings found on existing older structures. The edge of the door opening has an increased inward bend compared to the rest of the HMLT base. This inward bend results in binding on the socket and on the original wrench as shown in Figure 3.3.18 (left). The stack socket was not tested on the new HMLT base designs, but it is fairly likely that it would work since the new bases are larger and the clearances on the smaller legacy bases were close for the stack socket fitting.

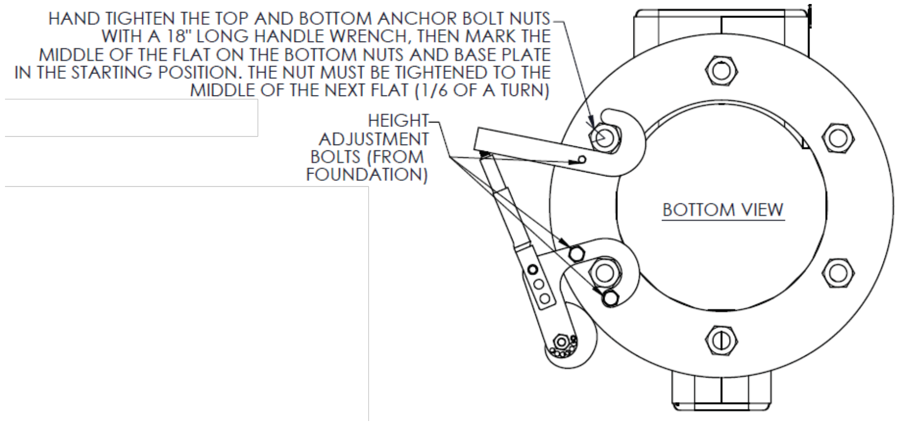
Millerbernd J Wrench Field Testing

Millerbernd, the HMLT manufacturer, designed and produced a hydraulic wrench for tightening the bottom nuts as detailed in Figure 3.3.19 and 3.3.20.



Millerbernd 2019

Figure 3.3.19. Top view of Millerbernd wrench operation



Millerbernd 2019

Figure 3.3.20. Bottom view of Millerbernd wrench operation

The wrench frame assembly uses a hydraulic jack to rotate the J wrench, which turns the bottom nuts tight. The wrench frame reacts off an adjacent bottom nut and the outside of the base sidewall. In this configuration, the reaction bottom nut is a theoretical pinned connection, and the wall reaction is a theoretical roller connection. Adjustment of the Millerbernd wrench is completed by adjusting the cam in the back of the wrench frame against the wall of the HMLT. As torqueing takes place, the hydraulic jack extends, rotating around the mounting bolt on the wrench frame to maintain contact with the J wrench. A 10,000 psi electric hydraulic pump powers the hydraulic cylinder.

During operation of the Millerbernd wrench, MnDOT staff noted several limitations. Neither a pressure gauge nor calibration were provided with the wrench assembly. While the plans indicate 1/6 of a turn, this specification may not be valid for maintenance on existing HMLTs and could result in damage to the wrench with the torque required to turn existing nuts to the required pre-tension. Additionally, if a contractor failed to use turn-of-nut, they may assume that the wrench is calibrated for the correct torque values on the nuts and overstress the frame, as observed by MnDOT workers.

Clearance under HMLT bases was also a defined limitation according to MnDOT personnel. Due to the thickness of the J wrench and existing conditions of in-place high mast tower foundations, such as: limited standoff distances, short anchor rod projections, embedded bottom nuts in the concrete foundation tops, and interference with electrical conduits, the J wrench could only be placed on a limited number of HMLT anchorages.

While a contractor was using the Millerbernd wrench, the frame of the wrench bent. Yielding appeared to occur primarily in the tensile controlled region of the frame at one of the leveling screw holes (Figure 3.3.21).

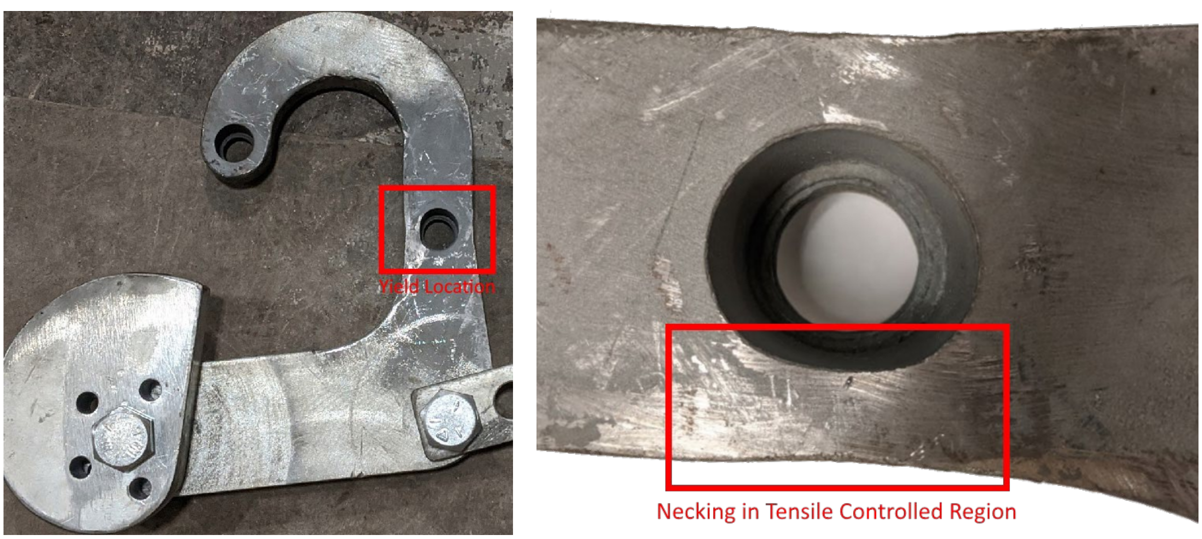


Figure 3.3.21. Yield location (left) and necking detail (right)

The yielded region surface differences from the edge of the leveling hole to the edge of the wrench were measured with a dial indicator (Figures 3.3.22).

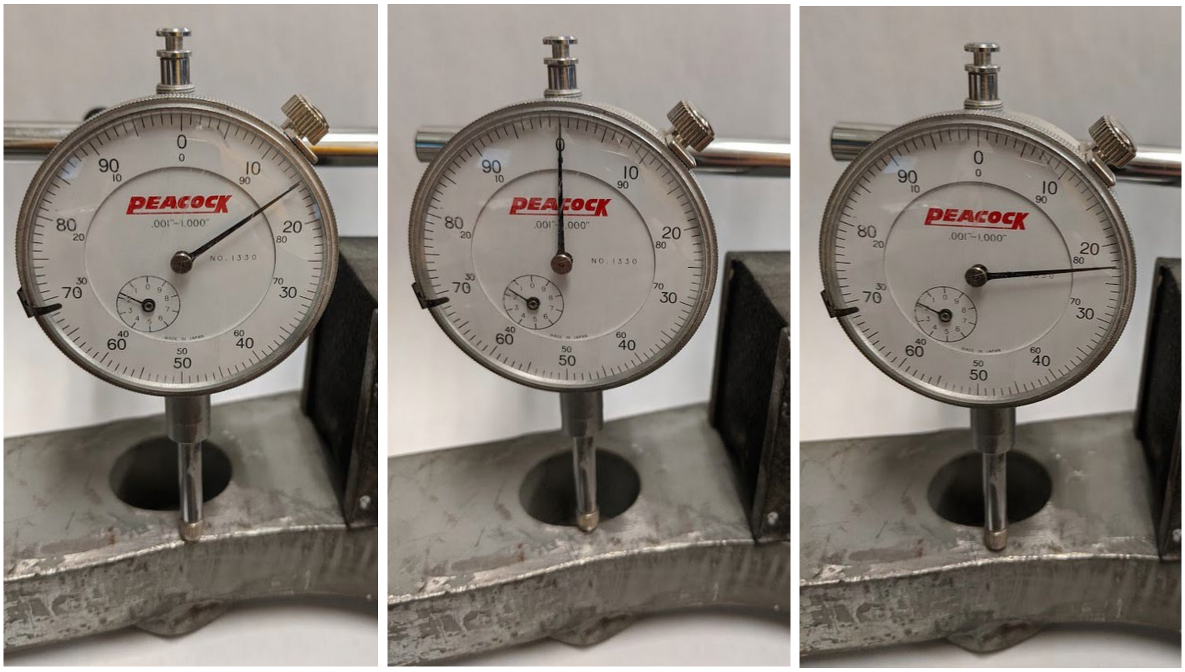


Figure 3.3.22. Distance measurement at hole edge, high point, frame edge (from left to right)

Near the edge of the hole, there was a 0.023" difference from the high spot of the region; toward the edge, there was a 0.008" difference, which approximately matched the rest of the wrench. The decrease in the cross sectional area near the hole likely indicates that the yielding was primarily due to stress concentrations. The galvanized coating makes any repairs on the current wrench difficult.

The movement range of the Millerbernd wrench was modeled in CADD (Figure 3.3.23) to determine the range of operating angles and any associated geometric constraints.

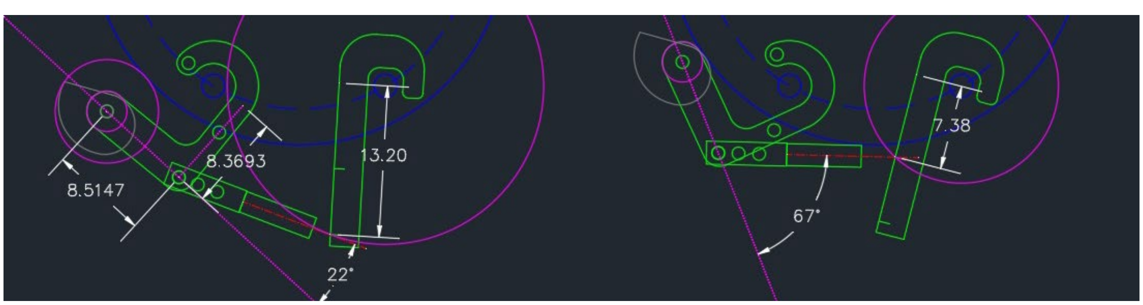


Figure 3.3.23. CADD model of Millerbernd wrench geometry and operations

The wrench was modeled on the older base design to investigate the limits for maintenance purposes. It was found that the operating angle range of the wrench was 22 to 67 degrees from the plane between the back cam and clevis holes. The 22-degree operating angle occurred with full cam extension and on the furthest J wrench slot. The 67-degree operating angle occurred with the minimum cam extension and on the closest J wrench slot.

The wrench frame was analyzed as a simply supported moment frame/lever with the cam end acting as the roller and the bolted connection end acting as a pin. While these assumptions are idealized, they can give an approximate idea of the internal forces in the wrench frame. The steel grade in all wrench parts was assumed to be grade 50, since it is the same as the HMLT structures that Millerbernd produces. An FEM was considered for analysis, but with the mesh size required to model stress concentrations and the time required to create the model, it was decided that using empirical relationships on a simplified model would be sufficient. Table 3.3.1 indicates the maximum operating force to yield the wrench frame.

Table 3.3.4. Wrench frame forces at hole section for 5,500 lb force and varying operation angles

			Pj (lbs): 5500		
			Fy (ksi): 50		(ASTM A572)
Pj angle (deg)	**Ve (lb)**	**Te (lb)**	**Me (lb")**	**σ Edge (ksi)**	**σ Interior (ksi)**
22	5099.511	7159.847	16675.4	37.9611	50.14101
27	4900.536	7397.484	16024.75	37.05437	49.3622
32	4664.265	7578.82	15252.15	35.86562	48.20772
37	4392.495	7702.478	14363.46	34.40392	46.68634
42	4087.297	7767.515	13365.46	32.68038	44.80965
47	3750.991	7773.436	12265.74	30.70812	42.59194
52	3386.138	7720.197	11072.67	28.50216	40.05007
57	2995.515	7608.203	9795.333	26.07928	37.2034
62	2582.094	7438.305	8443.446	23.45792	34.07359
67	2149.021	7211.798	7027.299	20.65803	30.68446

Table 3.3.2 indicates the minimum and maximum possible torque that could be applied to the nut from the J wrench.

Table 3.3.5. Pressure, force, torque, required thickness limitations, and frame factor of safety of 2

Bore ID (in): 1.13 (Enerpac RC55)
Max Lever Length (in): 13.2
Min Lever Length (in): 7.210338 (7.4*cos(13deg))
Wrench Thickness F.S. : 2

Pressure (psi)	Force (lbs)	Min Torque (ft-lbs)	Max Torque (ft-lbs)	Req. J Wrench Thk. (in)	Current Frame F.S.
500	501.4375	301	552	0.25	11.00
1000	1002.875	603	1103	0.51	5.50
1500	1504.312	904	1655	0.76	3.67
2000	2005.75	1205	2206	1.02	2.75
2500	2507.187	1506	2758	1.27	2.20
2600	2607.475	1567	2868	1.32	2.12
2700	2707.762	1627	2979	1.37	2.04
2800	2808.05	1687	3089	1.42	1.96
2900	2908.337	1748	3199	1.47	1.90
3000	3008.625	1808	3309	1.53	1.83
3100	3108.912	1868	3420	1.58	1.77
3200	3209.2	1928	3530	1.63	1.72
3300	3309.487	1989	3640	1.68	1.67
3400	3409.775	2049	3751	1.73	1.62
3500	3510.062	2109	3861	1.78	1.57
4000	4011.5	2410	4413	2.03	1.38
4500	4512.937	2712	4964	2.29	1.22
5000	5014.375	3013	5516	2.54	1.10
5500	5515.812	3314	6067	2.80	1.00
6000	6017.249	3616	6619	3.05	0.92
6500	6518.687	3917	7171	3.30	0.85

Table 3.3.2 also indicates the required thickness of the J wrench for a given torque value with an included factor of safety of 2 and the factor of safety on the frame with the applied force.

Note that Tables 3.3.1 and 3.3.2 are from a simplified analysis of the members without torsional, strain hardening, or intensive stress concentration impacts considered. While conservative assumptions were made during analysis, the failure values at a factor of safety of 1 should likely not be approached to avoid further damage to the current Millerbernd wrench frame. Note that Table 3.3.2 shows a theoretical pressure-torque relationship and has not been directly calibrated.

Looking into Table 3.3.1, the suspected failure mode from visual inspection and measurements was confirmed. For the stress at the interior of the hole, there is an empirical multiplier of 2.05 due to stress concentrations (Hibbeler 2017). While the flexural stresses are not at maximum at the edge of the hole, the stress concentration multiplier is enough to offset the difference, resulting in yielding at a 5,500 lb load from the hydraulic jack at a 22-degree operating angle. It is likely the contractor using the wrench applied approximately 6,000-8,000 lbs of force or 3,600-8,800 lb-ft of torque to yield the wrench frame. An exact value cannot be determined without knowing the exact configuration the wrench was in when it was damaged. Although these torque values are over the required value for lubricated HMLT structures, it is likely in an unlubricated case that these torque values could be reached to achieve the required turns. The contractor that yielded the wrench also did not have a maximum operating pressure for the tool and may have been mistaken on the calibration, resulting in the yielding.

In Table 3.3.2, the theoretical pressure and torque curves are compared to the minimum thickness of the J wrench and the factor of safety on the current wrench frame. The factor of safety on the frame is taken at an operation angle of 22 degrees, which results in the maximum torque values. All of the minimum torque values occur at operation angles between 41 and 67 degrees. Therefore, the closest slot on the J wrench will result in inefficient tightening. The factor of safety could be calibrated for the minimum torque values with lower angles; however, the closer slot on the J wrench results in higher axial forces for the same tightening torque. If the furthest slot in the J wrench is used, there is also less variability in the maximum torque values because the contact angle between the J wrench and the jack is closer to 90 degrees. Although the maximum torque of 2,980 ft-lbs is less than required, it should still sufficiently tension existing HMLT structures to prevent nut loosening. The minimum thickness for the J wrench with the current wrench frame could be 1.37", which is 0.4" and could help with the clearance issues encountered during maintenance. The reduced thickness of the J wrench would make the factor of safety the same for the whole Millerbernd wrench assembly if a factor of safety of 2 is desired.

Millerbernd J Wrench Field Analysis

After analysis, the Millerbernd wrench was tested in the field. Figure 3.3.24 shows the wrench set up for operation in the in the closest setting, and Figure 3.3.25 show the setup in the farthest setting.

Figure 3.3.24. Millerbernd wrench operation at closest setting

Figure 3.3.25. Millerbernd wrench operation at farthest setting

Much like the HYTORC hydraulic torque wrench, there were also clearance issues with the Millerbernd wrench, for both the wrench frame and the J wrench. The wrench frame could only be placed on four of the six bottom nuts due to the electrical conduit placement in the foundation as shown in Figure 3.3.26 (left).

Figure 3.3.26. Clearance Issues with conduit placement (left) and with foundation finishing (right)

The J wrench itself was only able to service one of the six bottom nuts. The location of the electrical conduit and the thickness of the wrench affected the placement of the J wrench. If the J wrench was milled down ½", it could fit under the same nuts as the wrench frame; however, the thickness presented a challenge with the concrete finishing on the foundation being rough, as shown in Figure 3.3.26 (right).

Because of the design limitations, the Millerbernd wrench may not be the ideal option for maintenance on HMLTs. Further discussions with Millerbernd indicated that they no longer intended to produce the wrench, so it will likely not be used for subsequent installations.

Slug Wrench

MnDOT's Electrical Services Section (ESS) currently uses a slug wrench, which is a wrench that is placed on the leveling nuts and struck with a 16 pound sledge hammer to re-tension HMLT structures from the leveling nuts. Slug or striking wrenches generally result in a pre-tension error of approximately 50% (Garlich and Thorkildsen 2005), and it is unlikely that they would reach the full 60% yield pre-tension with the full effort of a worker. However, the MnDOT slug wrench was investigated at HMLT TW06A 1 at the I-35 and TH 280 interchange. This HMLT is the older base design with a six-bolt pattern, and it is the same one that the Millerbernd wrench and the HYTORC stack socket were investigated against previous to this. Figure 3.3.27 (left) and (right) summarize the turn results of the tightening procedure and the method used, respectively.

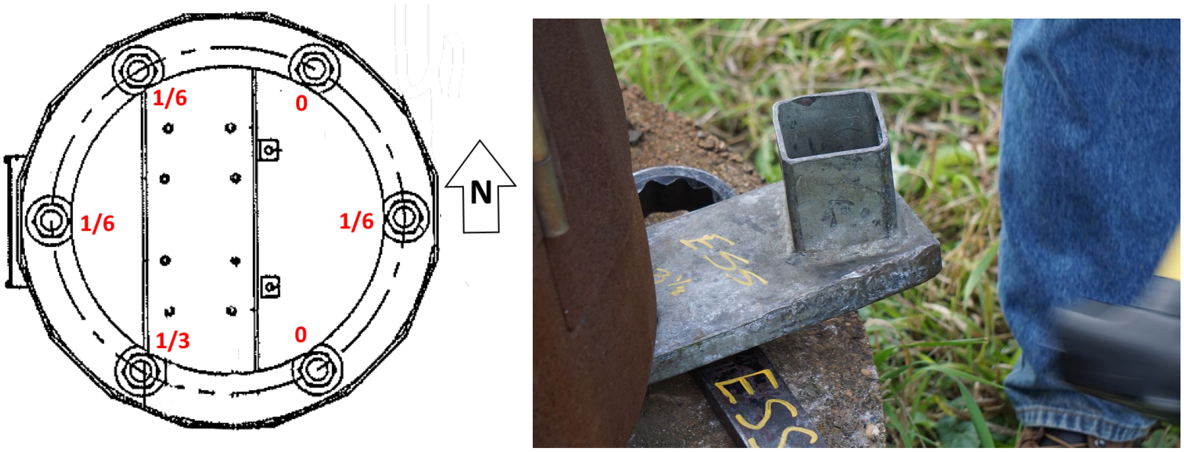


Figure 3.3.27. Final nut turns from original position (left) and striking wrench use (right)

The retightening process on the leveling nuts consisted of two steps, first breaking a nut loose in the opposite direction, then retightening up against the baseplate. This was performed for each nut individually with the MnDOT ESS slug wrench.

The first breaking loose step was used to make sure that the nut could be chased back up the bolt. The ESS closed spanner was used to prop up the slug wrench while striking due to the standoff distance. It may be beneficial for maintenance personnel to have varying sizes of plate steel with them if this method is used, to smoothly prop up the slug wrench.

All of the nuts were turned as far as they would go with the full amount of energy that could be put into the slug wrench. Full tightening strength was used, because it is unlikely enough energy could be put into the nut from this setup to yield the anchor bolt, considering the unlubricated condition. Figure 3.3.27 left shows the final turns achieved from the starting position of each nut on the HMLT base. Two of the six nuts could not be broken loose and were assumed to either be sufficiently pre-tensioned or rusted in place.

Of the four remaining nuts, three turned 1/6th of a turn and one turned 1/3rd of a turn. The turn values are fairly excessive, even from what was calculated, possibly indicating that they were initially torqued less than expected. If the slug wrench option is further pursued as a maintenance option for HMLTs, more research will be put into the maximum energy that can be achieved with a slug wrench, more wrench options, and a refined procedure for the handbook.

Maintenance serviceability may be improved with further iterations of the hydraulic torque wrench designs. In addition to the clearance issues on current HMLTs, MnDOT maintenance workers expressed concerns about bringing all of the required equipment to some light towers in remote locations, especially since the pump for the HYTORC wrench requires fairly constant voltage for accuracy. Field experience demonstrated that the pump sometimes struggled to operate using a generator and would not run off vehicle inverters. One of the MnDOT workers noted a transformer that plugs into the HMLT power outlet could be an option, but would result in high amperages after the voltage reduction.

Overall, the hydraulic wrenches that can be used for maintenance will likely not be able to service every nut on every post and are fairly difficult/frustrating to operate in the close quarters of the older base design. For maintenance, the slug wrench may be the best option for HMLTs with the older base design. If a very low clearance jack was used, the post could be jacked up to the proper pre-tension and the leveling nuts tightened, but finding a low enough clearance jack is unlikely.

3.4 Interviews and Feedback on Specifications

3.4.1 MnDOT Structures Maintenance Workers (Overhead Signs)

To investigate maintenance on overhead sign structures, workers from the MnDOT structure maintenance section were interviewed over their experience retightening anchor bolts on both cantilever and bridge truss structures. Pat O'Brien and his crew gave feedback on the maintenance procedure experienced in the previous summer, stating that it was fairly straightforward and not too burdensome, even though the nuts had to be removed and replaced from the structure. Before the new procedures, the crew generally didn't use any methodology and went around tightening loose nuts with a TorcUp hydraulic wrench. When asked about difficulties implementing new procedures, the primary issue was the applicability to all structures. By Pat's estimation, the maintenance procedure could not be completed on about a third to half of the existing structures in the MnDOT metro district due to the condition of the rods. In their experience, the bridge maintenance crew stated that they had broken off a couple studs due to the nut being rusted in place. To this degree, they requested that a max loosening torque for structures be calculated and recorded, to avoid breaking off studs during maintenance. Finally, the crew commented that checking and servicing the leveling nuts on many structures is not possible due to debris, clearance, and the wire mesh rodent guards.

3.4.2 MnDOT Metro District Traffic Office Lighting Operations –Lighting Construction Inspectors

For High Mast Light Towers (HMLTs), Light Poles and Traffic Signals, Metro District Lighting Operations lighting construction inspectors were interviewed. Since the installation procedures for HMLTs, traffic signal and light poles are still being developed, during the interviews no specific feedback was provided on revised steps. Though the specifications were still being developed, the lighting construction inspectors were able to feedback on the current procedures. They asserted that using turn of nut method inside the pole bases is impractical because it is very difficult to fully access the top nuts with full size manual type wrenches necessary to make the required turns and to see the required turns. This difficulty is especially true once the pole wiring is in place. Much like the overhead signs, leveling nuts are also difficult to access on lighting poles. Figure 3.3.27 (Left) shows a sample stainless steel light pole base brought in to demonstrate the clearance issues. Figure 3.3.27 (left) and (right) illustrate that the exterior overhang makes observation of leveling washers under the structure difficult. Figure 3.3.27(Left) also shows the 12 inch long offset flat specialty wrench made by the pole manufacturer that is used to snug tighten the leveling nuts of stainless steel light poles because of the baseplate overhang that covers the leveling nuts. The specialty wrench is a stamped wrench, cold-punch from sheet metal. Because they are not forged or heat treated the open ends will spread easily under forces greater than the snug tight condition. The hydraulic wrench is pictured for reference in Figure 3.3.27 (Left). In the inspectors' experience, the specialty wrench tends to bend under repeated uses when used in conjunction with a pipe extension, and is not designed to use for final turn of nut. The pole manufacturer's instructions state to use the specialty wrench for snug tight condition only. There was a consensus among the Metro District construction lighting inspectors that the base design for standard stainless steel light poles is less than ideal for anchor rod tightening. However, figuring out a retightening solution presents the most efficient design option since any change to the base design would need to be AASHTO MASH crash tested, an expensive process.

Figure 3.3.27: Exterior of Light Pole Base (Left) and Interior of base (Right)

For inspections, it was brought up that having the contractor fill out a form for every light pole, and HMLT installed is not feasible with the personnel available. Building on this fact, in the inspectors' experience, they are not always informed when pole installations are taking place on the project. To alleviate the workload, lighting construction inspectors requested that a method for inspecting structures after installation be developed and a consolidated form created. Finally, it was pointed out that the anchor rod tightening specification based off of the AASHTO LRFD specifications, needs to be simplified since contractors tend to get discouraged and ignore it if parts of specification are difficult or not possible to complete.

3.4.3 MnDOT Bridge Asset Management (Overhead Signs)

Bridge asset management performs the majority of inspections and cataloging of overhead signs in the MnDOT metro district. For this interview, Michael Cremin was available and Douglas Maki submitted a filled out questionnaire. Annually, Michael stated that MnDOT inspects and catalogs around 500 structures, with approximately 2,500 total structures in the Metro District. With the age range of structures, Michael noted that inspectors have difficulty identifying the grade of anchor rods, since many are rusted, were installed with old specifications, and are often not marked with the grade on the top. When asked about previous practices, it was indicated that contractors would often "put a little extra" torque than what was specified, thinking that it would help the connection. This indicates that it needs to be made clear to the contractor that exceeding the specification is just as damaging, if not more, as under tightening. Oftentimes during inspections, Michael experienced anchor rods with over 1/8" of a gap between some leveling washers and the baseplate. In his notes, Douglas indicates that the old maintenance operations were 'not a permanent fix' and the old specification was written assuming all of the nuts were grade 36. No turn of nut was used and the AASHTO procedures were not followed before the new procedures. Much like the lighting workers, both Michael and Douglas also indicated that the inspection resources for the structures maintenance is "spread thin" and that the field installation sheet is too cumbersome. During installation of a new sign truss structure on I94, it was observed that the procedures were pretty quick to follow with the hydraulic wrench, and the contractor was able to reopen the road in a timely manner. However, it was also observed that with the sign trusses, one side often has to be adjusted to affix the sign truss to the pole/s, possibly bringing the final installation out of plumb. Finally, Douglas said that it would be nice to have some alternatives to the approved lubricant, since contractors often do not carry it with them.

3.4.4 Hydraulic Wrench Manufacturer

Along with MnDOT personnel, Glenn Lickness, a representative for a manufacturer of hydraulic wrenches, also attended the interviews and offered feedback on the specifications. One of the important aspects that Glenn touched on was the obscurity of the term “snug tight.” He asserted that in manufacturing, snug tight is generally connoted as hand tight. The Metro District lighting construction inspectors and structure maintenance inspectors agreed that this terminology was confusing to contractors, and even among themselves they had different definitions. Glenn recommended that the snug tight value be referred to as a “proof” or “initial” torque in order to avoid confusion. He also recommended that the specification table be ordered in the sequence of steps, since there was some confusion on when to perform the steps by contractors he observed. Along with feedback on the specifications, Glenn provided information on the capabilities of the HYTORC hydraulic wrench system. He covered the fact that the pump is sensitive to the cold and it’s important to have the correct type of oil in it for the season. He also brought up that the HYTORC washer could help with the fatigue loosening and would be safer than normal wrench operation, since a reaction bar is not used. The HYTORC washer helping with fatigue would match up with literature and other proprietary non slip washers, since the angle of the interaction of the HYTORC washer is higher than the thread pitch angle, helping to avoid rotation and loss of pretension in the bolt.

3.5 Concluding Points

- **Clearances in structures presented difficulties with following turn-of-nut specifications**

With lighting and traffic signal structures, there were significant difficulties implementing the turn-of-nut specification due to clearance issues within the post bases. On OH sign structures, both the turn-of-nut and torque procedures were fairly straightforward. It would likely to be beneficial to separate the procedures into overhead sign and lighting/traffic signal categories.

- **The clarity of specifications could be improved**

In many cases, there were miscommunications on the procedure steps, lubrication, torque, and turns. It is likely that the specification could be simplified with more illustrated figures of the steps. The different specification deviations should also be investigated to estimate the effect they have on the final anchor rod pre-tension scatter.

- **Maintenance and new installations likely need different specifications**

Performing maintenance retightening on structures presented different challenges and required several different approaches when compared to new installations. It would likely be beneficial to further subdivide the specification between maintenance and installation procedures.

- **Appears new procedures work for overhead sign structures**

  After inspection of six OH sign structures, it appears that the new procedures are performing well and no under pre-tensioned anchor rods were recorded.

- **48-hour retightening torque is difficult to perform**

  In both installation and maintenance, retightening connections after 48 hours presents a drain on resources and should be investigated further to estimate its effect on pre-tension loss.

- **A method for inspection after installation would likely be beneficial for resources.**

CHAPTER 4: OVERHEAD SIGN MONITORING RESULTS

4.1 Methodology

4.1.1 Specimen and Instrumentation

4.1.1.1 Setup

The instrumented sign was a cantilevered OH sign structure in Rosedale, Minnesota, shown in Figure 4.1.1 (left).

Figure 4.1.1 Instrumented sign post (left) and data logger cabinet (right)

Installation and instrumentation took place in August 2017. The post and anchor rods were instrumented with three wire resistance strain gauges. On the post, eight 6 mm temperature-compensated foil strain gauges produced by Tokyo Sokki Kenkyujo Co., Ltd. were affixed. The anchor rods were bored 4 ½" down into the approximate grip length and instrumented with a bolt strain gauge series BTM 6 mm produced by the same company. In addition, an R. M. Young Company 05103V wind monitor was fixed to the top of the sign structure. The anchor rods were Grade 55, 2 ¼" diameter, and the post was a MnDOT Type 4 with a Type A base (MnDOT n.d.). A Campbell Scientific data logger (Figure 4.1.1 right) was utilized for data collection with a sampling rate of 100 Hz. For more information on the installation, see the previous study (Chen et al. 2018).

Figure 4.1.2 shows a simplified elevation view of the structure with dimensions and a section of the roadway as shown from the decreasing, southbound direction on the roadway.

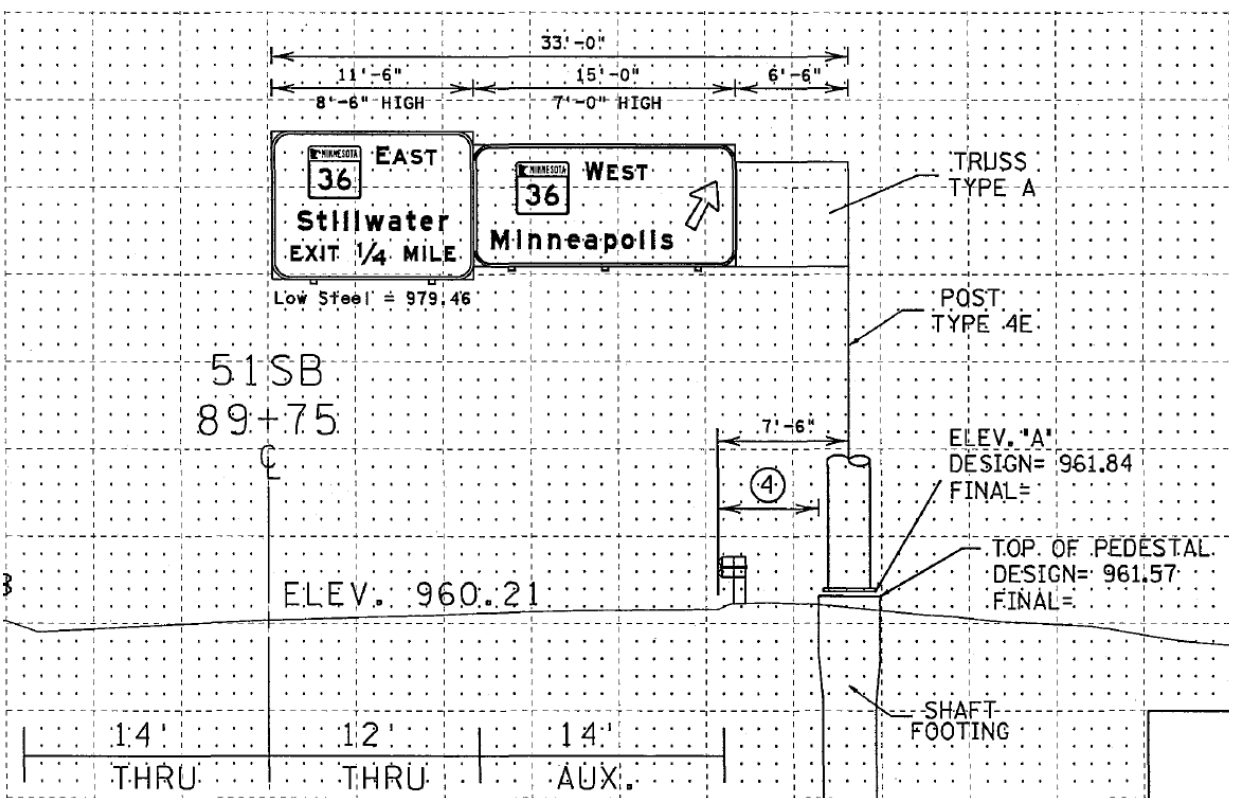


Figure 4.1.2. Elevation of sign structure from southbound travel

Figure 4.1.3 shows reference locations for all gauges with an elevation and plan view of the post base.

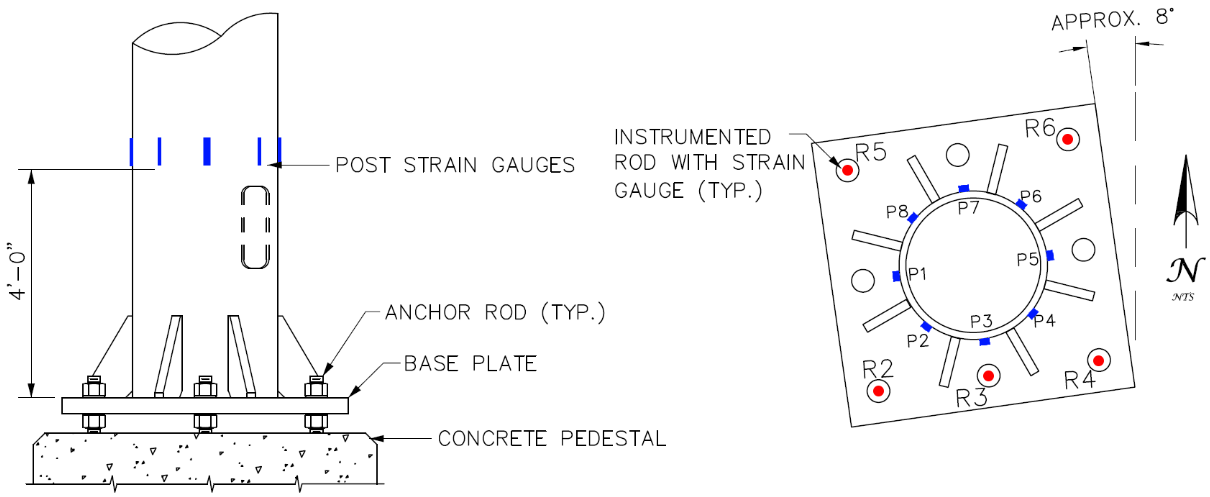


Figure 4.1.3. Lower post instrumentation elevation view (left) and post base instrumentation plan view (right)

For specific dimensions, see MnDOT Standard Plan 5-297.764 (MnDOT 2019).

4.1.1.2 Data Collection History

An effective structural monitoring system must be continuously kept up and is often constrained by environmental factors. This was true with data collection on the instrumented post in Minneapolis. Oftentimes, maintenance could not be completed due to winter weather and other factors.

The sign data collection system was installed in August 2017 with the data from that year reported in the Phase I report (Chen et al. 2018). As of July 2018, only bolts 2 and 3 were transmitting data, likely due to intrusion of water into the other gauges. The gauges could not be replaced in the fall and winter due to weather constraints. In September and October of 2018, the data were corrupt due to an issue with the logger.

In mid-April through early May 2019, the data logger failed leading to missed data for parts of those months. Finally, in July 2019, the broken strain gauges were replaced in the field; however, the strain gauge in bolt 3 began to drift after the others were replaced, and it stopped working completely in early August 2019. This could have been due to a wiring problem in the cabinet after adjusting the other bolts.

In late January 2020 through early February 2020, the power supply to the logger shorted out and three weeks of data were lost due to inaccessibility of the site.

4.1.2 Data Processing and Derivation

For processing, computer code developed by the research team was utilized for more efficient data processing due to the data being collected continuously at 100 Hz for the past two and a half years. The computer code was based on ASTM E1049-85 (ASTM 2017), which is the rainflow counting method for fatigue stress cycles.

After rainflow counting was completed, a lognormal probability density function curve was fitted to a histogram of the rainflow counts for each day, and the equivalent stress range was found by taking the third moment of the function as outlined by Lassen and Recho (2006) in Fatigue Life Analyses of Welded Structures.

Using a log normal PDF was chosen over Miner's rule due to it being able to more effectively model the probability of occurrences than Miner's cumulative damage method. After processing, the equivalent stress range for all anchor rods ended up being close to 0.5 ksi. This value is far lower than the AASHTO constant amplitude life limit of 7 ksi. However, after further research into the equivalent stress range concept, the practice was deemed unsuitable for investigating pre-tension loss for anchor rod connections.

To understand why an equivalent stress range for anchor rod pre-tension loss is unsuitable, it is helpful to first understand a simplified derivation of a typical equivalent stress range damage fraction and the general design S-N curves. For a more in depth derivation, refer to Miner's original paper (Miner 1945). For both the Miner and other equivalent stress range concepts, they are dependent on empirical fatigue tests for specific details. This is in order to derive a damage fraction, as illustrated in Equation 4.1.

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C \tag{4.1}$$

In Equation 4.1, n_i is the number of cycles applied at a specific stress, N_i is the number of cycles to failure at a specific stress, and C is the damage fraction. If C is equal to 1, the detail has failed in theory. Equation 4.1 approximately quantifies the lifespan of a detail that is taken up from a specific stress range. Each stress range count and the corresponding damage fraction can then be summed to approximate if a certain detail has failed. Even if a probabilistic model is used, it is still dependent on an empirically derived damage fraction for determining equivalent stress ranges.

The unsuitability of the accepted fatigue damage concept for pre-tension loss arises from both the definition of fatigue damage and the empirically derived damage fraction. Firstly, the definition of fatigue damage is fairly binary; a detail is fractured or it is not. Whether it is complete failure, crack propagation, or crack initiation, fatigue damage is defined. For pre-tension loss, it is a little more difficult to define, and possibly complete loss of pre-tension or a loss of a defined interval of strain could be utilized, but there are no existing fatigue tests that are performed in that manner. Even if a "failure" pre-tension is defined, an S-N curve for each pre-tension would be required since the number of cycles at a certain stress range would also be dependent on the initial pre-tension force. Empirical derivation of such F-S-N curves would likely be difficult when considering the number of confounding variables, and especially pre-tension accuracy and long-term relaxation. The rainflow counting results from the anchor bolts and post are presented in the Concluding Points section of this chapter. From the rainflow plots, laboratory testing cycles were derived to approximate field conditions and monitor possible fatigue losses from the new procedures.

4.2 Data

4.2.1 Climate

Since the focus of this project was primarily the stress in the anchor rods, climate data focused on the long-term seasonal changes in anchor rod forces. To investigate long-term changes in the anchor rods, a daily average was taken for each day in the dataset. An average was chosen due to various daily temperature differentials, and these data would adequately represent anchor rod behavior over a long time period.

Throughout the year, anchor rods experienced, approximately, a 10 ksi stress differential from the summer to winter months. This is likely due to thermally induced stresses from expansion and contraction, but could also be due in part to resistance change in the strain gauges or wires. Long-term rod stresses also match up approximately with a theoretical daily temperature-induced stress based on material properties and connection stiffness. Figures 4.2.1 and 4.2.2 illustrate the long-term anchor rod stresses and theoretical temperature-induced stresses for half of the monitoring period each.

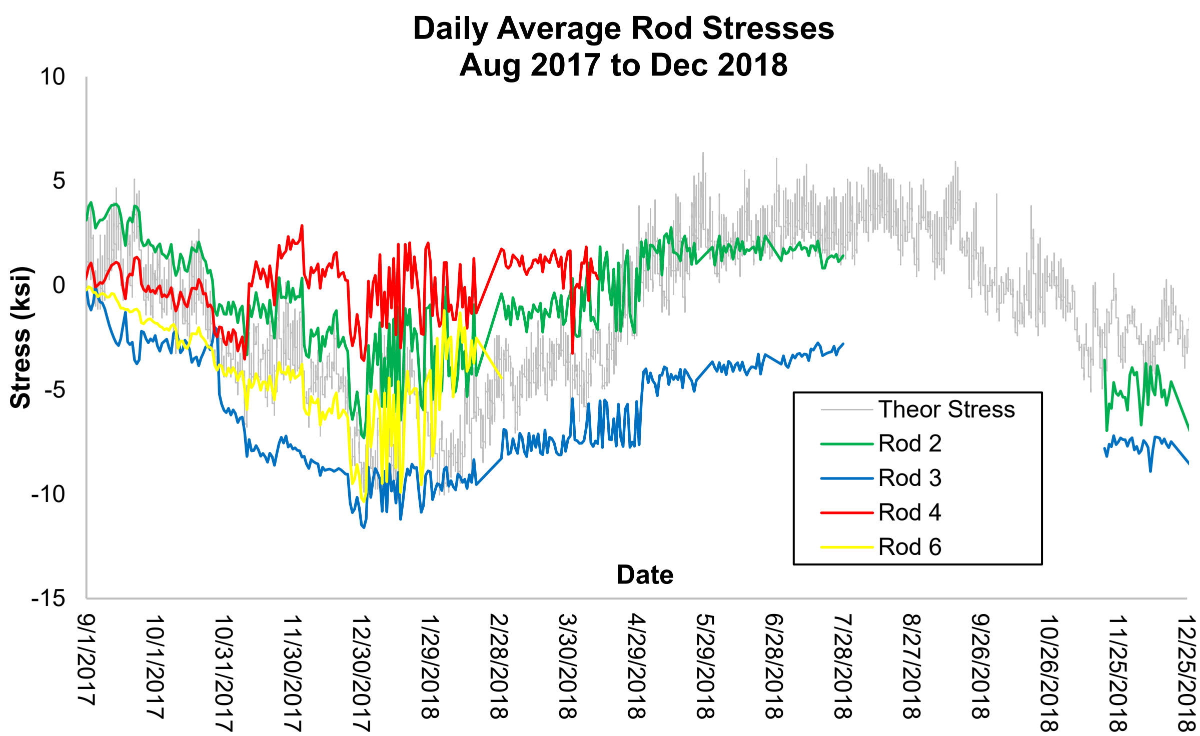


Figure 4.2.1. Long-term anchor rod stresses 8/2017–12/2018

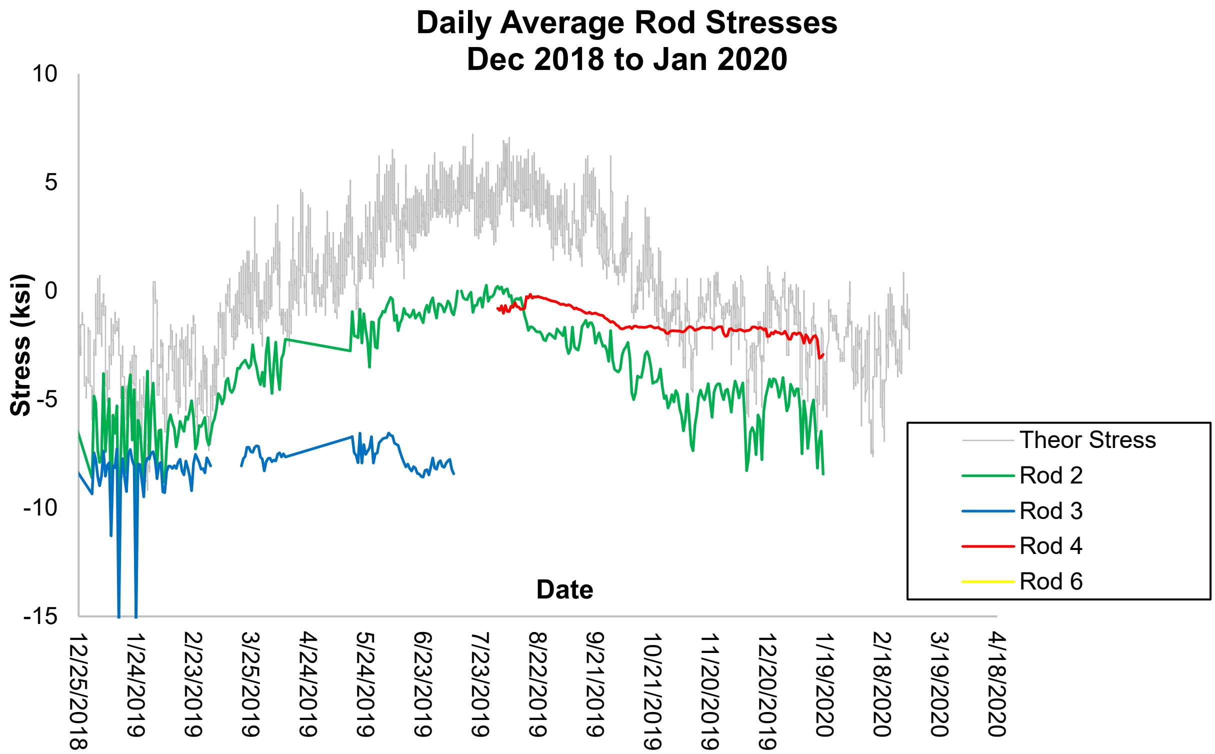


Figure 4.2.2. Long-term anchor rod stresses 12/2018–1/2020

For clarity, data are not included when anchor rod gauges failed. Another observation from the long-term rod stresses is that there is increased scatter in winter months and many gauges were observed to fail during this time period. It is hypothesized that the scatter is likely from snow and ice accumulating on the anchor rod gauges in addition to snow impacting gauges when a plow passed the installation. Enforcing this theory is the fact that all of the north facing gauges, which coincided with rods 5 and 6, failed first during the winter of 2017–18. The north facing part of the pole received the greatest snow impact from snowplows and likely resulted in premature failure of the rod-mounted gauges. Finally, the rod strain data does appear to drift away from the theoretical data. While this behavior could be due to relaxation or pre-tension loss, it is also likely that the resistance gauges are drifting over a long period of time and needs to be tested further in a laboratory environment to confirm any long-term loosening impacts.

4.2.2 Rainflow Curves

Rainflow counting N-S curves were developed for both the post gauges and the anchor rod gauges. *N* is the number or count of cycles, and *S* represents the stress or strain range. Figure 4.2.3 shows the N-S curve for the post gauges with 1 microstrain bins, and Figure 4.2.4 shows the N-S curve, in 0.925 ksi stress bins, for the anchor rod gauges that functioned the full year in 2018.

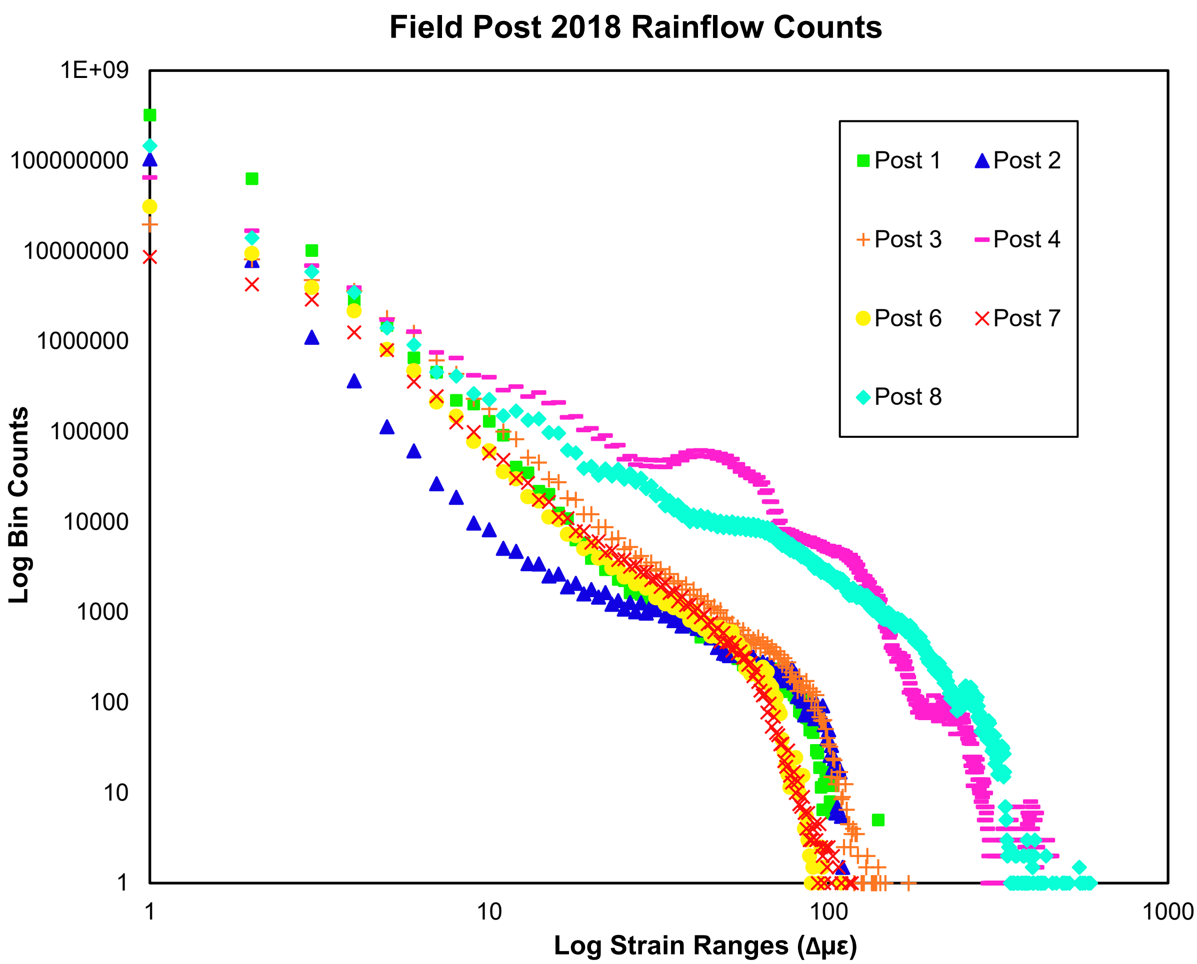


Figure 4.2.3. Field N-S curve for post stresses

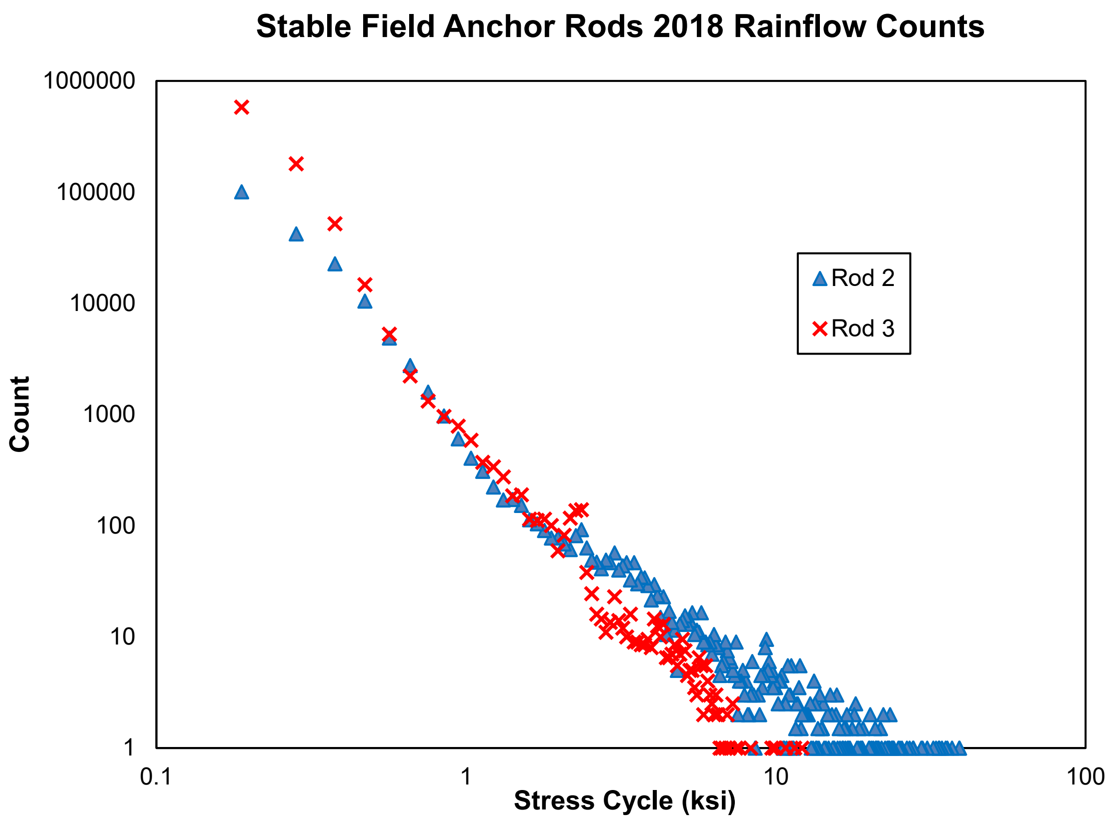


Figure 4.2.4. Field N-S curve for post stresses

Note that these plots are not S-N curves empirically derived for design purposes and instead represent the direct field stresses on the monitoring structure. Field N-S curves are generally represented in histograms, but for brevity and clarity, bins for multiple gauges are represented by points in Figures 4.2.3 and 4.2.4. Each point represents the maximum of its respective bin.

In Figure 4.2.3, the rainflow count of post strains for the maximum observed stresses were in post gauges 8 and 4 at approximately 600με. Gauges 4 and 8 were on opposite sides of the monitoring post, so it makes sense that they would both be maximum. Interestingly though, the two maximum gauges are not perpendicular with the sign/road direction and are closer to 45 degrees from perpendicular to the sign. Galloping or vortex shedding could be the reasoning for these results, or possibly the sign's natural frequency is in that direction. All other strain gauges experienced a maximum of about 100 με.

In addition to the post N-S curve, one was also constructed for the anchor rod stresses, shown in Figure 4.2.4 on a log-log plot. Both of the anchor rods that illustrated long-term stability, 2 and 3, were plotted, since the data for some of the other anchor rods were questionable. Rod 3 experienced a maximum stress differential of 10 ksi and rod 2 experienced a maximum stress differential of 40 ksi. However, there are a couple of additional confounding variables involved with the anchor rod gauges than with the post gauges.

As discussed in the previous Climate section, snowplows and snow likely had an impact on the gauges, likely disturbing the tops of the connections, which have shown to be sensitive to disturbances. Figure 4.2.5, taken with the structure monitoring camera, shows snow and ice on the gauges in late February 2020.

Figure 4.2.5. Snow and ice piled on anchor rod gauges

All of the large stress cycles were experienced during winter months. A 40 ksi stress reversal of rod 2 would also be unexpected given it was an exterior anchor rod. Previous experience in Phase I demonstrated that exterior anchor rods, like rod 2, are subjected to less stress than interior rods, like rod 3.

4.3 Concluding Points

- Long-term monitoring of anchor rods shows, approximately, a 10 ksi seasonal differential stress due to differential temperature impacts.
- Overall, this change would be enough to loosen anchor rods if tightened with the old specification of 480 ft-lbs. The differential may also play into long-term pre-tension loss, but the impact has yet to be definitively observed.
- There is downward drift in the anchor rod strain gauges of the sign structure.
- The downward drift may be pre-tension loss through relaxation or fatigue, but it is more likely that it is due to long-term drift of the resistance strain gauges. When rod gauge 3 failed in August 2019, the wires were stripped and it was found that they were corroded, which would impact the total resistance of the connection. Additionally, the post gauges, which are not in a pre-tensioned state, also have a slight downward drift, but it is difficult to make comparisons between the two given they are different sizes and types of resistance strain gauges.
- It may be more reliable to base laboratory testing on the forces that the post exerts on the anchor rods due to the reliability and number of functioning anchor rod gauges.

- For laboratory testing, it would likely be better to model the testing procedure off the forces that the post undergoes and therefore transfers to the anchor rods, instead of the anchor rods themselves, due to the level of uncertainty with the anchor rod gauges.
- Anchor rods have not lost significant pre-tension over the past two and a half years.
- Looking into the long-term data and after field inspections, it appears that the connections have remained sufficiently pre-tensioned over two and a half years, which is better than MnDOT's previous experience. The connections were also pre-tensioned with AASHTO turn of nut, which may indicate that the current specification is sufficient, but could just use improvement with its implementation and inspection.

CHAPTER 5: LABORATORY TESTING

5.1 Fatigue Testing

5.1.1 Methodology

5.1.1.1 Procedures

For fatigue testing, the primary goal was to investigate the impact that fatigue loading has on the anchor rod connections and to validate the field monitoring data. Two fatigue tests were completed with one replicating two years of in field loads and another to relate known AASHTO Constant Amplitude Fatigue Life (CAFL) curves to anchor rod pretension loss. Derivation of both procedures will be presented after the static testing results are covered.

For both fatigue tests, the anchor rods were pre-tensioned with an approach similar to that observed from field observations. First, the pole was checked for level and the top nuts were brought to hand tight. Leveling nuts were then tightened with a strap wrench to approximately 50 ft lbs, since a large enough open ended wrench was not available. Using a TorcUp hydraulic wrench, the top nuts were tightened in 20%, 60%, and 100% increments of the verification torque which is 3,300 ft lbs. A 48 hour retightening torque was not applied to investigate the impact of relaxation on the rods without retightening.

5.1.1.2 Fatigue Test Setup

Figure 5.1.1 outlines the base and anchor rod instrumentation. Figure 5.1.2 illustrates the post instrumentation and overall test setup. For further details on the loading block and post, refer to Schaeffer, et.al 2018. Numbering for the anchor rods starts in the upper left corner and moves clockwise around the post following conventional identification procedures. Strain measurements are acquired from three wire, quarter bridge resistance strain gauges produced by the Tokyo Sokki Kenkyujo Co. 6mm gauges were used on the post and standoff. Strain gauges on the standoff and stiffener toe were applied after the first, field replicated fatigue test. The anchor rod strain gauges are BTM series gauges from the same manufacturer. They are epoxied into the anchor rods in the grip length. Middle strain gauges on the post were affixed at the same distance from the base as the ones on the field monitoring structure. Figure 5.1.3 shows the standoff strain gauges and the top of the anchor rod strain gauges. Note that the standoff gauges were covered in butyl rubber for protection. Schaevitz AccuStar Inclinometers were used to monitor any nut turns on the lower four nuts as shown in Figure 5.1.3. The inclinometers were mounted on wood boards to avoid damaging the instruments during attachment to the nuts. The inclinometers measure around the center of the instrument, which from geometry would be equivalent to any nut turns observed. For turn verification, all nuts were also marked with turn lines after pre-tensioning on the top nut (Figure 5.1.4 Left) and the leveling nut (Figure 5.1.4 Right).

The post tested is a MnDOT legacy design used from 1995 to 2019. The post is a No.5 design on a Type B base plate. (MnDOT 2019) An exact steel strength was not specified, but it can range from 42ksi to 65ksi, per MnDOT specifications. Anchor rods are F1554 2 ½ inch diameter Grade 55, which presents a limiting case due to less available pre-tension force to be developed than with Grade 105 rods. Anchor rods were cast into a reinforced concrete loading block during previous research activities. The loading block is post tensioned to the laboratory strong floor with 100 kips on each post tensioning rod to provide an approximate fixed condition.

Loading is applied with a MTS Hydraulic Actuator (Figure 5.1.5 Left) to a HP section embedded in the end of the post. The MTS Actuator is fixed to a HSS steel frame post tensioned to the laboratory strong floor, shown in Figures 5.1.5a and b. A VTI Instruments EX1629A data collection system was used to collect both voltage and strain data while a VTI EX10SC was used to collect temperature data.

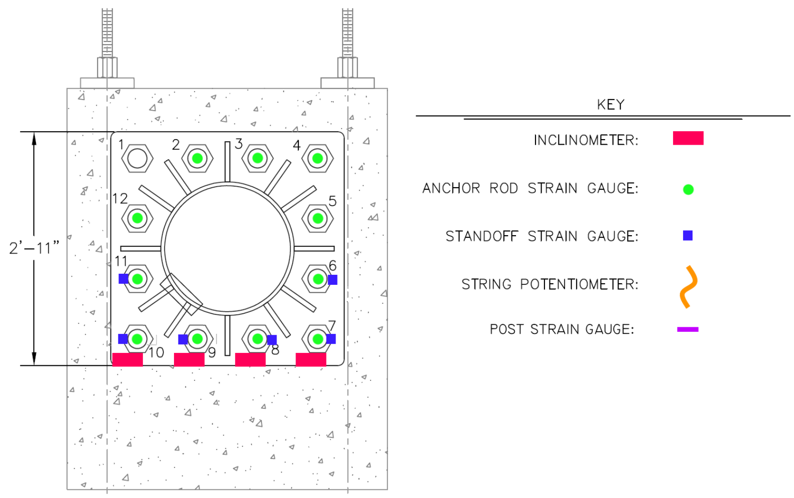


Figure 5.1.1: Base Instrumentation

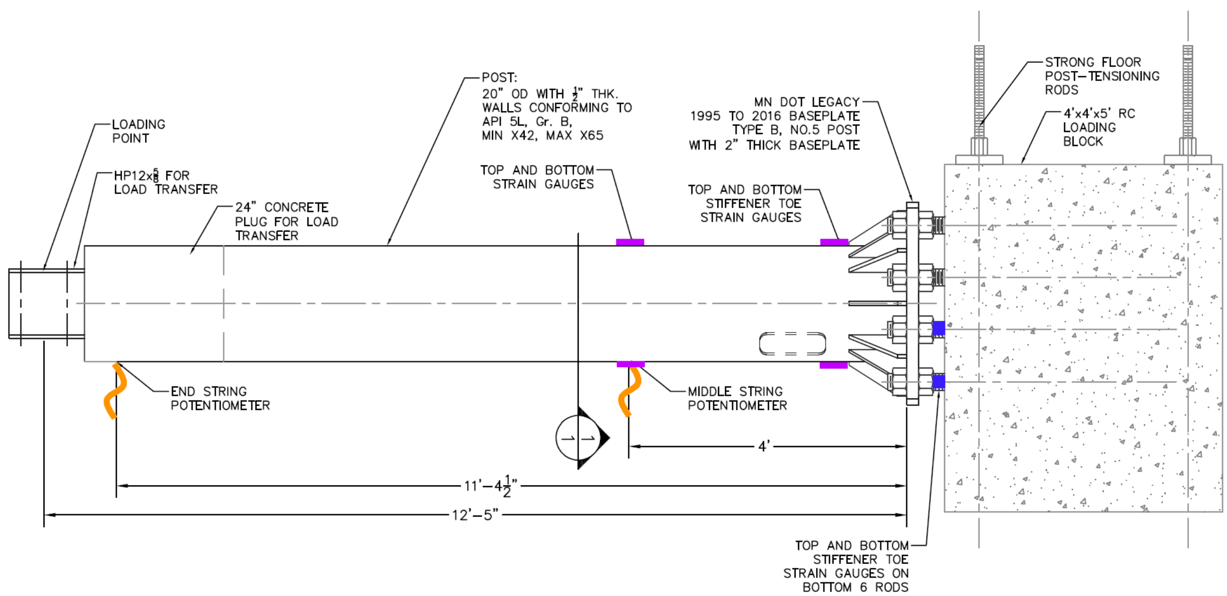


Figure 5.1.2: Post Instrumentation and Test Setup

Figure 5.1.3: Lower Post Instrumentation

Figure 5.1.4 (Left): Example Turn Marks after Tightening on Top and (Right) Leveling Nuts

Figure 5.1.5: (Left) MTS Hydraulic Actuator and (Right) Data Acquisition System and Loading Frame

5.1.2 Static Testing

Before fatigue testing, a relationship between the Hydraulic actuator and test sample response was acquired through static loading cycles. Note that in the following plots only the lower six anchor rods are shown for clarity.

Notation for the following sections will be taken facing the laboratory structure as shown in Figure 5.1.2. Tension will be considered as positive strains or stresses. Positive loads or displacements from the MTS indicate pushing down on the end of the post, inducing a negative moment at the base, theoretically putting the lower 6 anchor rods and bottom strain gauges into compression (negative), and inducing a downward (negative) displacement. The conversion from microstrain to ksi is με*0.029 for all components of this structure and strain measured is engineering, as opposed to true.

Figure 5.1.6 shows the static response of the anchor rod embedded strain gauges measuring the change in clamping force in the grip length in microstrain. Note that these changes are in addition to any pre-strain in the anchor rods from tightening. Referring to Figure 5.16 and 5.1.1, the middle bottom rods, 8 and 9, experience the greatest strain at around +/- 19 με and +/- 28με, respectively. Next, the corner rods, 7 and 10, experience strains at about +/- 9με. Finally, rods 6 and 11 experience a differential of +/- 6με. All grip length strains exhibited a linear response to the loading.

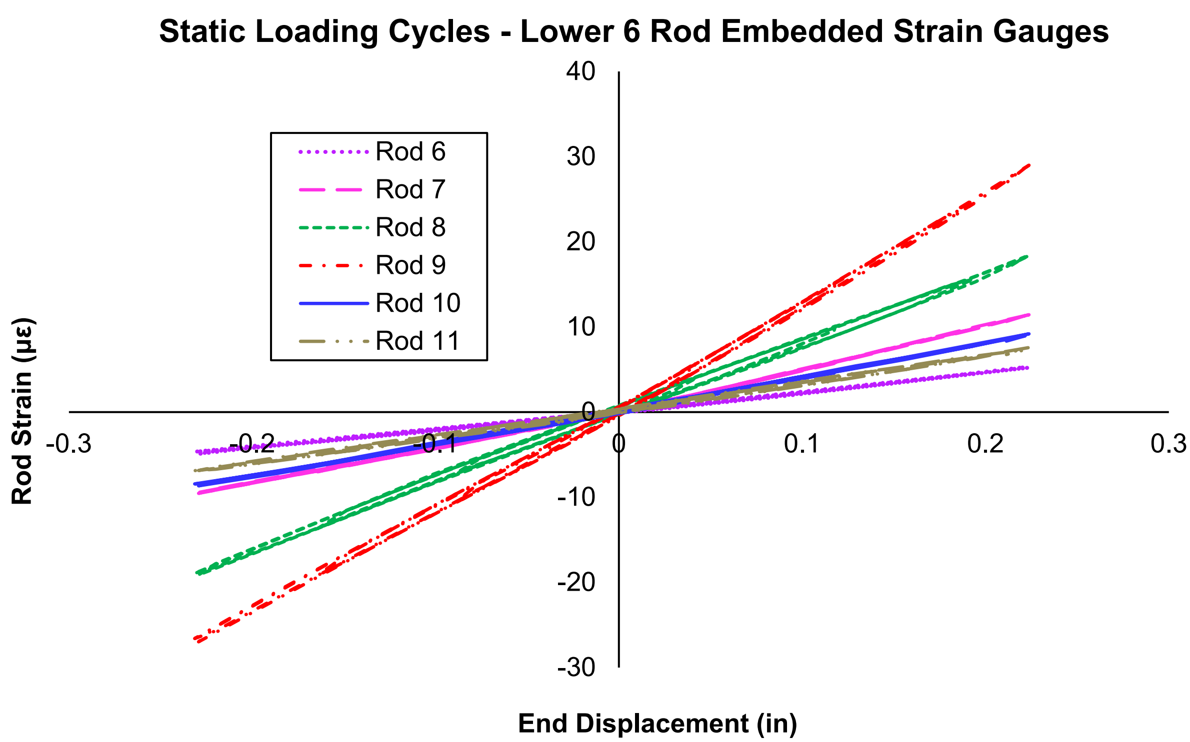


Figure 5.1.6: Anchor Rod Response to Static Loading

Figure 5.1.7 illustrates the strains in the lower six rod standoffs. The middle lower rods, 8 and 9, experience around five times the strain expierenced by the corner or upper middle rods that are closer to the neutral axis of the post base. This strain increase is about double the differential observed in the grip lengths. The strains for SO11 and SO6 overalp, which indicated the strain gauges were mounted fairly consistently between the two. Interestingly, the corner rods experience an inverse force of what would be expected from the loading and all the curves show some nonliearity.

In addition to the recorded strains, theoretical strains for the anchor rods, calculated with the assumption of a uniform strain distribution, are plotted. The theoretical strain curves are based on the induced baseplate moment related to the displacement of the end of the lab testing post.

Strains in the rod standoffs likey don't match the theoretical strains due to the non uniform baseplate stiffness. Standoff distances in the lower middle anchor rods, the critial case, experienced approximately 5 times greater than theoretical strain. The corner rods are farther out on the square baseplate and furthur from the stiffners, possibly causing a stiffness decrease, shifting the force transfer primariliy to the middle anchor rods. Since the baseplate stiffness is not uniform, this may also explain the non-linearity of loading transferred to the foundation. With regards to loosening from base shear forces though, the square design may be benefical, since the corner rods would prevent the structure from slipping with the middle rods taking the majority of the axial forces. Design of a square base may need to be reevaluated, as the current practice derived with a linear strain distribution in AISC Design Guide 1, the AASHTO reccomendation for design, does not accurately represent applied forces on the anchor rods.(AISC 2006)

The stiffness ratio, C, of the conections in the laboratory range from 0.20 to 0.54 and average to 0.38. The stiffness ratio is much larger than the theoretical stiffness calculated as 0.26 from Equation 2.8 and may indicate that a greater than expected amout of stress is being transferred to the anchor rod grip lengths than anticipated. However, AASHTO does not allow for pre-tension to be considered in design, so this condition would likey be a servicability concern and not a failure concern. Much like the embedded anchor rod strain gauges, there may also be some degree of scatter with the strain data from the standoff due to gauge mounting differences. Compiled with the error in the anchor rod gauges, this may also explain the higher than anticitapted stiffness ratios. The standoff strains, on average, exhibiting higher and more uniform strains than the standoff distances suggests that the post is acting composite with the pre-tensioned structural connections.

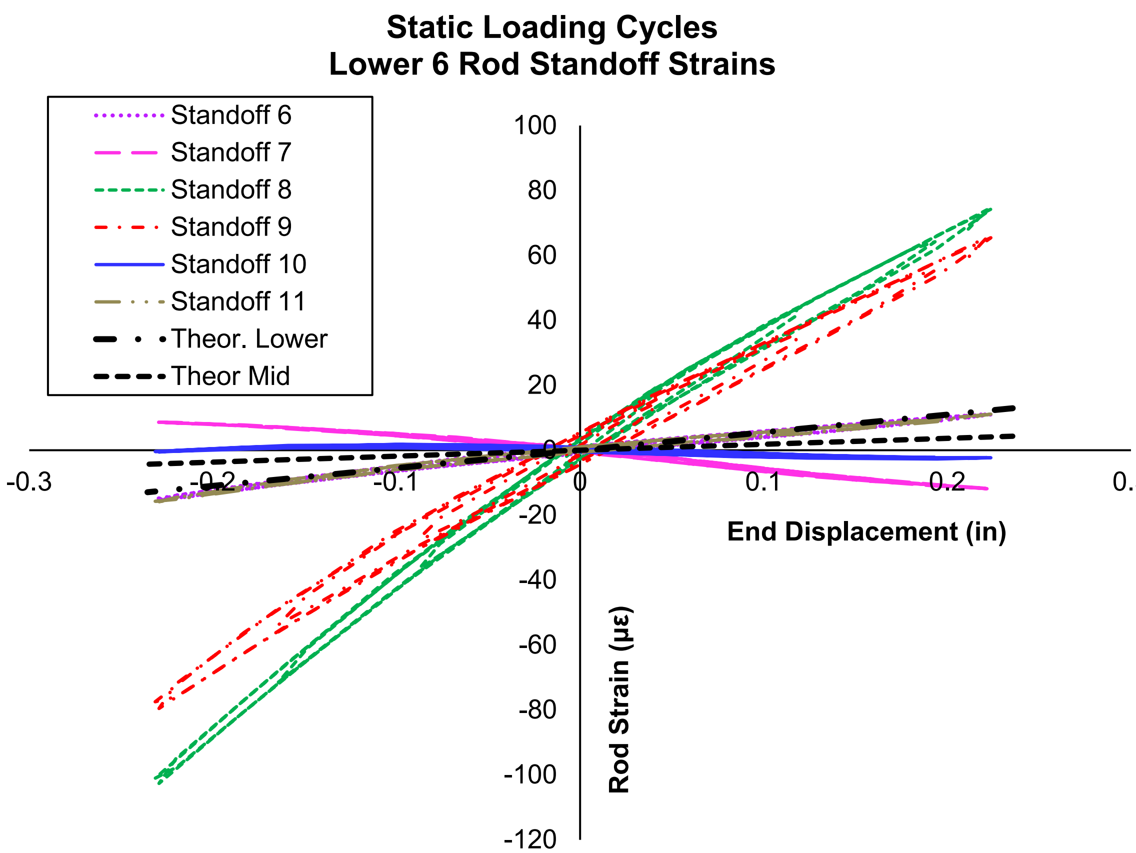


Figure 5.1.7: Standoff Strains Response from Static Loading

Figure 5.1.8 shows the post strain response under static loading. Both the gauges mounted at the stiffener toes and at four feet above the baseplate are shown. Note that the strains at the stiffener toes presented the limiting condition for the signpost, reaching a maximum of 640 με, or six times larger than the maximum strain experienced by the standoff rods and twenty times larger than the maximum strain in the anchor rods. These results align with James' testing in 1996, where the base to post weld connection failed multiple times and had to be repaired with welds throughout the testing. (James et al. 1996) Figure 5.1.8 shows both the top and bottom gauges, so matching gauges acting inversely is desired. Theoretical values are also plotted for the bottom gauges, but not shown for the top gauges due to redundancy. The theoretical values were calculated using a traditional mechanics approach. For the middle 4’ gauges, the theoretical value matches experimental measurements relatively well, however the stiffener toe strain values are approximately 1.5 times the theoretical value due to the presence of stress concentrations. The discrepancy approximately matches up with the design assumptions in AASHTO and other research findings for stress concentrations around weld toes. (Lassen and Recho 2006) From Figures 5.1.7 and 5.1.8, it is likely that the post stresses at the weld details will generally govern for Overhead signs when compared to the anchor rods, even if base stiffness is considered.

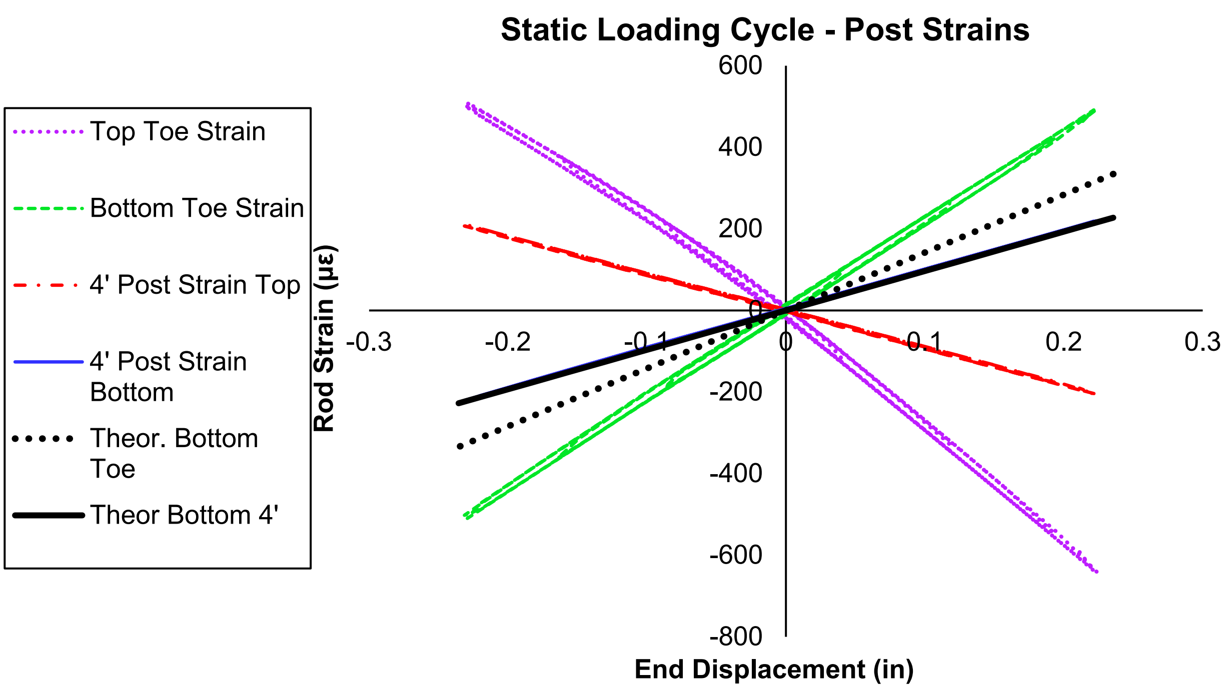


Figure 5.1.8: Post Strain Response from Static Loading

5.1.3 Field Replicated Fatigue

5.1.3.1 Derivation and Methodology

As discussed in the field monitoring section, an equivalent stress range for anchor rod pretension loss cannot be developed with the assumptions in the current S-N practices for traditional fatigue testing since a damage fraction for pre-tension loss has not been derived. Due to the equivalent stress range limitations, a laboratory testing procedure that approximately replicated the field loading conditions was derived from the in-field rainflow counting results. Field stresses from the post were used to approximate the post loading on the anchor rods because the field anchor rod S-N curves were questionable and the base design of the field monitoring structure is different than the laboratory specimen. The field stresses were replicated with an approximate summation procedure, setting pre-determined strains to induce with the MTS hydraulic actuator, and then finding how many cycles in the field occurred in the strain ranges to program the MTS accordingly. In the summation procedure, counts under 4 $\mu\varepsilon$ (0.116ksi) were disregarded considering noise in the strain gauges and because it was hypothesized that the significantly lower stress ranges would not have a major impact on loosening. Also, the counts for lower strain ranges would have required approximately a month to replicate at low stresses. Equation

Figure 5.1.1 outlines the laboratory testing cycles compared to the summed stress range cycles. After summing the strain range bin counts for each post gauge, an average of the fitted exponential curves was taken to derive a laboratory testing curve. After deriving the field curve, it was normalized for the total number of days recorded in the year and broken into individual cycles by the highest stress range. The MTS was then programmed with the respective number of cycles in each loop. Table 5.1.1 outlines the final laboratory testing cycles used from the field stresses.

Though the laboratory testing curve appears to not be conservative for post gauges 4 and 8, all of the field cycles that fell into the bins are tested at a higher one. For example, if the field post experienced 50 bins of 321Δμε stress reversals, the 50 bins would be tested at 640με in the laboratory, since 321Δμε is in the next higher bin. Approximating from traditional fatigue testing, damage fractions tend to increase exponentially, so while the summed counts of the post 4 and 8 are higher, it is likely that the pre-tension loss "damage" has been adequately accounted for using the prescribed method.

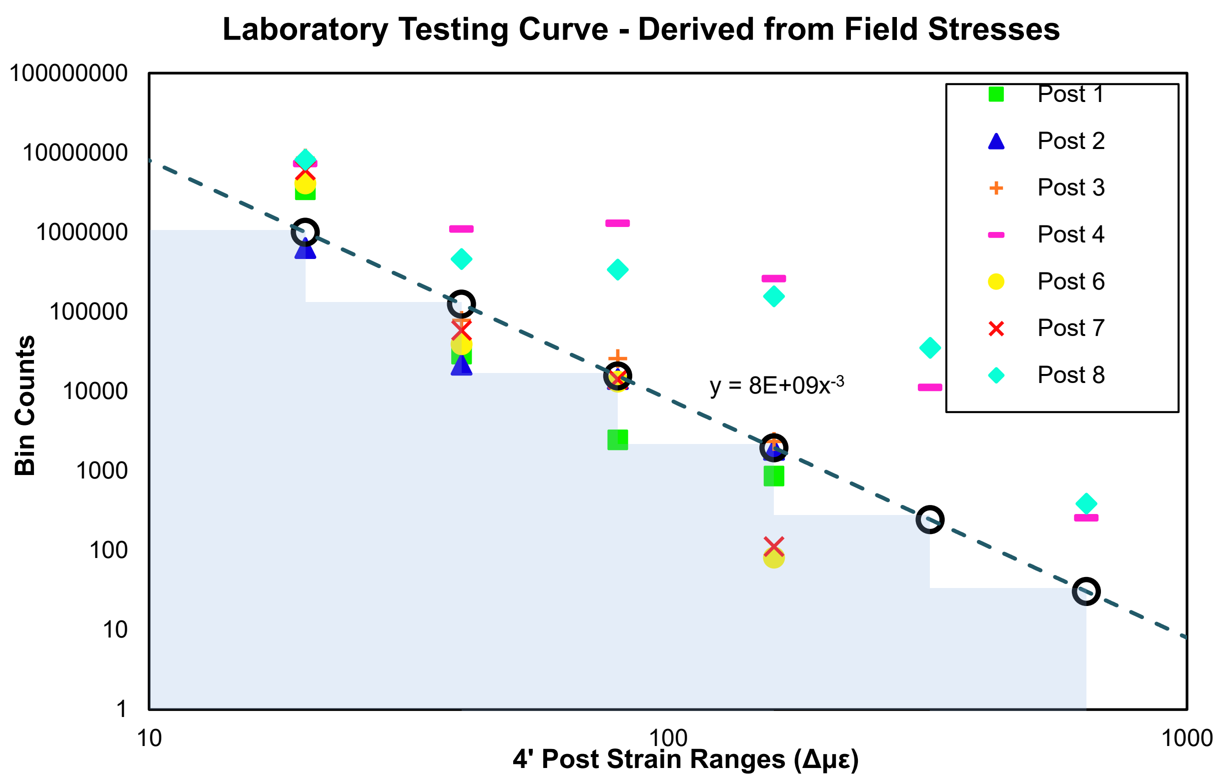


Figure 5.1.9: Field Derived Laboratory Testing Curve

Table 5.1.1: Field Derived Laboratory Testing Cycles

Desired Test Stress Range (ue)	Field Curve Cycles (Using c=E8*ε^-3)	Yearly Cycle Correction (193/365 days recorded)	Single Laboratory Test Loop Cycle Count	Cycles to Replicate # Years = 2	Stroke +	Stroke -	+/- Load (kip)	Loading Rate (Hz)
20	1000000.00	1689815	**32497**	3379688	0.013	-0.013	0.323	5
40	125000.00	211227	**4063**	422552	0.026	-0.026	0.646	3
80	15625.00	26404	**508**	52832	0.051	-0.051	1.293	2
160	1953.13	3301	**64**	6656	0.103	-0.103	2.585	1.5
320	244.14	413	**8**	832	0.205	-0.205	5.170	1.25
640	30.52	52	**1**	104	0.410	-0.410	10.340	1

Total Cycles:3862664

Loops to Test:104

5.1.3.2 Results

Table 5.1.2 shows the results of the field replicated fatigue loading test. In Table 5.1.2, the strains after initial pre-tension, 48 hour relaxation, fatigue testing, and immediate losses (when the nut was removed) are illustrated for a full overview of the strain losses in the sign post. The absolute pre-tension losses in the anchor rods was recorded during nut removal to validate losses recorded at the end of fatigue testing.

From Table 5.1.2 one can observe that there is a fair amount of variability in the individual rod results in all regards. Due to the strain variability, each anchor rod's performance is compared relative to itself in terms of percent losses. Additionally, rods 3 and 5 were not considered due to sensitivity issues and the gauge for rod 4 was broken off while repositioning the wrench to remove nut 3, but it still returned loosening data

After the 48 hour relaxation there was an average loss of -4.1% from the initial pre-strain. Note that the 48 hour losses were recorded after tightening, so the "initial pre-strain" does not account for the immediate losses after tightening. Immediate losses in conjunction with the 48 hour losses will be discussed further in a following section. After the fatigue test, there was an average overall loss, including the relaxation, of -6.2% for the anchor rods, with rod 12 having the greatest overall losses of -16% of the initial strain. When directly loosened, the total average losses amounted to -14% of the initial pre-strain. The immediate loosening value was taken as more reliable than the final fatigue value, because the absolute strain loss could be immediately measured practically without temperature and strain drift impacts. Taking the immediate loosening values was also more conservative, as the average recorded losses were approximately double that of the ones recorded at the end of the fatigue test. It is suspected the connection for rod 6 was not connected completely while loosening, as it "gained" nearly 400με from the initial value, and was disregarded from respective averages.

All inclinometers indicated negligible turns after the fatigue test, with a maximum change of 0.025degrees (1/14,500 of a turn), which is within the error range of the inclinometers. These minimal turns indicate that a transverse loading is likely not a primary loosening mechanism, as expected.

An average of 36% of all losses, considering the immediate loosening came from losses recorded 48 hours after the initial pre-tensioning. If the end of the fatigue losses are considered, initial relaxation is 74% of all losses. The fatigue test was started 5 days after the initial pre-tensioning however, so it is likely there was additional unrecorded relaxation before commencing fatigue testing.

Finally, the replicated 2 years of fatigue loss was far less than the strain drop observed on the field monitoring post. This may indicate that a majority of the perceived strain losses in the field are due to drift of the strain gages and not actual loss, and considering the strain drift observed in the laboratory, this would be fairly reasonable. It is likely that relaxation and temperature have a far greater impact on pre-tension loss than fatigue loading, if anchor rods are properly pre-tensioned. Finally, much like traditional fatigue testing, it is likely that the lower strain ranges have little impact on anchor rod pre-tension loss

Table 5.1.2: Field Replicated Fatigue Summary

	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6	Rod 7	Rod 8	Rod 9	Rod 10	Rod 11	Rod 12
Initial Pretension (με):	720	7	989	74	820	648	688	914	468	580	520
48 hr relax (με):	687	-8	959	39	783	606	662	892	467	519	511
% Change of initial pretension:	-5%	-222%	-3%	-47%	-5%	-6%	-4%	-2%	0%	-11%	-2%
Strain After Fatigue Test (με):	689	-20	846	39	777	597	669	853	481	488	514
% Change of initial pretension:	-4%	-394%	-14%	-47%	-5%	-8%	-3%	-7%	3%	-16%	-1%
Immediate Loosening (με):	614	22	913	8	1214	505	633	896	445	466	344
% Change of initial pretension:	-15%	223%	-8%	-89%	48%	-22%	-8%	-2%	-5%	-20%	-34%
% Between fatigue and loosening:	11%	210%	-8%	80%	-56%	15%	5%	-5%	7%	5%	33%
% Relaxation losses to fatigue losses	31%	-99%	39%	53%	-10%	29%	47%	127%	2%	53%	5%

	Avg.	Stdev
% Total test losses	-6.2%	6%
% Direct loosening:	-14%	23%
% Loss from Relaxation:	36.0%	40%

*Averages disregard rolts 3 and 5

5.1.4 AASHTO Reference Service Life Replicated Fatigue

5.1.4.1 Derivation and Methodology

After observing that the field derived fatigue testing had little impact on the pre-tension loss in the anchor rods, it was decided that fatigue testing of the anchor rods would be related back to a typical AASHTO CAFL of a known detail. This approach was conceptualized for a couple of reasons. Firstly, the time required to replicate the field stresses on the post using the prior procedures takes about a week per year replicated, and it was not feasible to replicate a full 25 year, or greater, design life. Second, testing at a known CAFL could give a reference benchmark for loosening that could be related back to accepted standards. Third, and lastly, the applied fatigue stress will be higher, hopefully resulting in definitive, quantifiable fatigue induced pre-tension loss in the anchor rods.

The standoff anchor rods acted as the baseline AASHTO CAFL. However, they were not stressed to their full CAFL, since the post stresses controlled the loading. Using the equations and procedures in AASHTO, the post at the stiffener toe has a finite life constant, A, of 11*10^8 ksi^3 and a threshold, ΔF, of 7ksi. The anchor rods have threshold of 7ksi. Both of the details are AASHTO fatigue curve D. Referring to the static testing, the anchor rods standoff distances could not be brought to their threshold, or CAFL, stress due to concerns about prematurely failing the post, as with James' research. (James et al. 1996) Rods 8 and 9, the middle lower rods standoffs were the controlling anchor rod stresses. The lower two anchor rod standoff distances were stressed to an average of 166 Δμε (4.8 ksi, aimed for AASHTO Fatigue Curve CAFL E), which corresponded to 1088 Δμε (31.6ksi) at the weld toes of the structure and 51Δμε (1.5ksi) in the anchor rod grip lengths of rods 8 and 9. Equation 11.9.3-2 from AASHTO LRFD – SLTS (AASHTO 2015) was then used to find the theoretical cycles to failure for the post in a finite life, since the 32ksi stress reversal is greater than the CAFL for the details of 7ksi. With a 32 ksi stress reversal, AASHTO allowed for 33,600 cycles until failure, which was deemed overly conservative due to the stress concentration factor included in the recorded laboratory sample strains. Therefore, a theoretical stiffener toe stress was calculated as 666Δμε (20ksi) and used. This was deemed valid because the AASHTO Fatigue Stress Concentration factor, Kf from Table 11.9.3.1-1, for the detail was calculated at 2.28, which allows for the calculated stress to be used. Using the pure AASHTO calculation procedure, the finite lifespan of the post was found to be 137500 cycles of 20ksi stress reversals at the top and bottom stiffener toes. After derivation, the sample was tested using a displacement controlled sinusoidal loading with an MTS stroke amplitude of 0.28" (Static loading of +/-6.9 kips) at a frequency of 1Hz. A major crack or failure was not discovered after 800,000 cycles (9 straight days of testing) of the loading outlined above, or about 6 times the AASHTO design life.

Since no cracks were discovered, it was decided to load the standoff strains to their full AASHTO CAFL of 7ksi. In this fatigue test, the critical anchor rod standoffs were strained at 250 Δμε (7.25ksi), which corresponds to post-stiffener toes strains of 1500Δμε (43.5 ksi), and anchor rod grip length strains of 75 Δμε (2.2 ksi). Additionally, the loading was changed from displacement to load controlled in order to account for any softening of the details from fatigue. The loading was applied by the MTS in a sinusoidal pattern with an amplitude of 11.5kips (0.46" under static loading) from the MTS at 1Hz. This test ran for 9450 cycles before failing the top cross beam of the testing frame in fatigue. It is likely that the fatigue crack in the frame had initiated during the previous fatigue test and was brought to failure by the higher loading cycles. Overall, the final cycles brought the total design AASHTO life 6.2 times greater than allowed in the code for the post details. To check for micro cracking, dye penetrant testing was utilized, but was inconclusive due to the rough surface on the post, and possible crack locations being longitudinal to welds, which made proper cleaning difficult.

5.1.4.2 Results

Summary of the final fatigue test losses are presented in Table 5.1.3. Much like the field replicated fatigue loading, a strain-time plot is not presented.

Pre-tension loss, on average, in the anchor rods was similar to the field replicated fatigue, only differing by 2 percent for both the total recorded test losses and the immediate loosening recorded losses. In the second fatigue test there appears to be less pre-tension losses from initial relaxation. However, the AASHTO replicated fatigue was started a day after the 48 hour relaxation, so some of the losses could be from relaxation and creep, as opposed to the field replicated fatigue test that was started a week after the initial pre-tensioning. It is likely that fatigue loading does not have a large impact on connection loosening if they are properly pre-tensioned. Comparable fatigue loading in the Phase 1 study (Schaeffer, et al. 2018) resulted in anchor rod loosening after 6000 cycles when the anchor rods were pre-tensioned with MnDOT's old specification, of 480 ft.lbs, or 14% of the AASHTO recommended verification torque.

Table 5.1.3: AASHTO Reference Detail Replicated Fatigue Pre-Tension Loss Summary

	Rod 2	Rod 3	Rod 5	Rod 6	Rod 7	Rod 8	Rod 9	Rod 10	Rod 11	Rod 12
Initial Pretension (με):	798	-5	50	1011	261	791	1088	857	529	276
48 hr relax (με):	775	-2	73	954	265	789	1008	832	504	251
% Change of initial pretension:	-3%	-53%	47%	-6%	2%	0%	-7%	-3%	-5%	-9%
Strain After Fatigue Test (με):	768	9	73	987	263	747	999	829	523	167
% Change of initial pretension:	-4%	-267%	47%	-2%	1%	-6%	-8%	-3%	-1%	-40%
Immediate Loosening (με):	676	25	8	950	242	721	986	810	402	131
% Change of initial pretension:	-15%	-568%	-84%	-6%	-7%	-9%	-9%	-5%	-24%	-52%
% Between fatigue and loosening:	12%	-181%	89%	4%	8%	4%	1%	2%	23%	21%
% Relaxation losses to fatigue losses	19%	9%	-56%	95%	-23%	2%	79%	54%	20%	17%

	Avg	Stdev
% Total test losses	-7.9%	24%
% Direct loosening:	-16.1%	16%
% Loss from Relaxation:	14.0%	42%

5.1.5 Sign Post Response to Anchor Rod Pre-Tensioning

Direct torque tension curves are not presented for the strain gauges inside the anchor rods due to their variability and error concerns. As with the fatigue testing section, relative results will primarily be presented.

5.1.5.1 Standoff Distances

The baseplate stiffness impact that was discussed in the static testing section was further observed during pre-tensioning of the anchor rods. Before pre-tensioning, the leveling nuts were torqued to approximately 50 ft.lbs. Shown in Figure 5.1.10, the standoff strains were fairly impacted by the pre-tensioning, especially the corner rods, that experienced an average of 1050με (30.5ksi tension). The middle anchor rods experienced an average increase of -163με (4.7ksi compression). The unexpected behavior of the standoff strains may be due to the baseplate stiffness, making the corner rods "pull" the sign base in, putting the middle rods into compression. Most of the strain increase occurs during the 20%, or approximately snug tight phase of pre-tensioning. This behavior suggests that it is critical to properly tighten the leveling nuts. The rod standoffs may have experienced less strain increase if the leveling nuts had been tightened against the baseplate to a greater degree, but is unlikely because the corner rods, further from the stiffeners, exhibited the greatest increase, while the increase in the other standoffs were approximately negligible. The non-uniform baseplate stiffness is likely influencing this behavior, but would need further investigation.

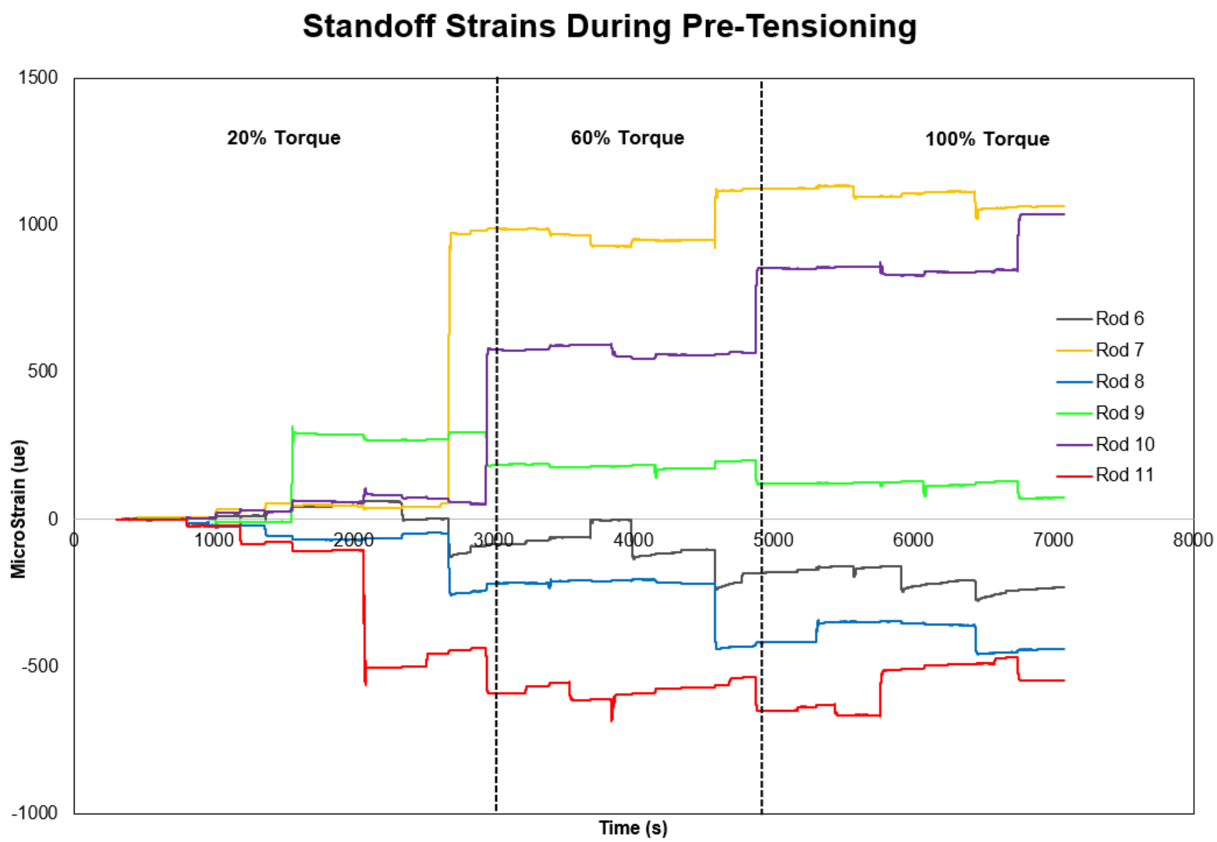


Figure 5.1.10: Standoff Strains during Anchor Rod Pre-Tensioning

5.1.5.2 Relative Relaxation

Experience in the field indicated that 48 hour retightening of anchor rods is fairly difficult and resource intensive, especially if the structure is mounted in the median of a highway. To investigate if the 48 hour retightening step can be removed, relaxation of the anchor rods was recorded on the laboratory sign post specimen. Relaxation was also investigated for Skidmore anchor rod pre-tensioning results, however, due to different connection stiffness properties, the results will not be presented, since the Skidmore relaxations would likely be lower than actual connections would experience. Note that the relaxation data are limited in the scope to the anchor rod and base thickness of the laboratory structure, and it may not necessarily directly extrapolate to other base conditions. In addition, the anchor rods referred to as "retightened" were on the field replicated post and the "un-retightened" anchor rods were on the AASHTO reference replicated post. The reasoning for this order is because the original field replicated fatigue test did not have strain gauges mounted on the standoff distances. Before the field replicated fatigue, the anchor rod locations had been previously pre-tensioned, but the data logger was configured improperly. After the field replicated fatigue, the post was moved forward on the anchor rods 2 inches to allow for mounting of the standoff strain gauges, which moved the top and leveling nuts onto untightened areas of the anchor rods. There could also likely be error from reusing the nuts and washers, likely leading to greater relaxation in the field than observed in the laboratory.

Figures 5.1.11, and 5.1.12 present the relative relaxation data for the initial 30 minutes after pre-tensioning for both the retightened and tightened cases. Spaces in these data are for clarity and occurred when the strain gauges were disconnected to put the hydraulic wrench on, or work around the sign disturbed the gauge. Quick drops in the strains may have either been due to disturbances or impacted by tightening of the other anchor rods, so they are included for the sake of completeness. Data ends at different points for all of the anchor rods due to the tightening order. Finally, not all rods are included due to strain sensitivity causing excessive noise in the data for rods 5, 6, and 9.

All of the relative losses in Figure 5.1.11, the un-retightening relaxation, exhibit a power distribution. All of the losses are fairly widely scattered between the two approximate upper and lower loss limits. The loss limits were approximated from previous literature along with these data. (Yang and Dewolf 1999, Nijgh 2016) Both the power pattern and the losses match up fairly well with previous research. If a 50 year lifespan is considered for the upper limit relaxation, the anchor rods would lose 10% of the original pre-tension, with the lower limit of relaxation, an anchor rod might experience 45% total lifespan losses from relaxation. Due to the power distribution, the majority of the losses take place within the first week after tightening. Though results from tightening suggest that AASHTO and AISC are generally correct in recommending that connections are retightened after 48 hours, Figure 5.1.12 illustrates a conflicting point.

In Figure 5.1.12, showing the relaxation losses after the retightened case with the anchor rods, immediate relaxation exhibits greater consistency, and lifetime relaxation is limited to approximately 25% over the rod lifespan. This suggests that, if the anchor rods are retightened at any point, relaxation should be of a lower degree and of greater uniformity. These observations are confirmed by Nijgh from research at TU Delft where the relaxation of European structural bolts connections with different coating types was investigated. Nijgh found that galvanized structural bolts relaxed approximately half as much with a greater uniformity when they were retightened after 40 minutes. (Nijgh 2016) This behavior was observed without taking the nuts off, somewhat validating the proposed field retightening.

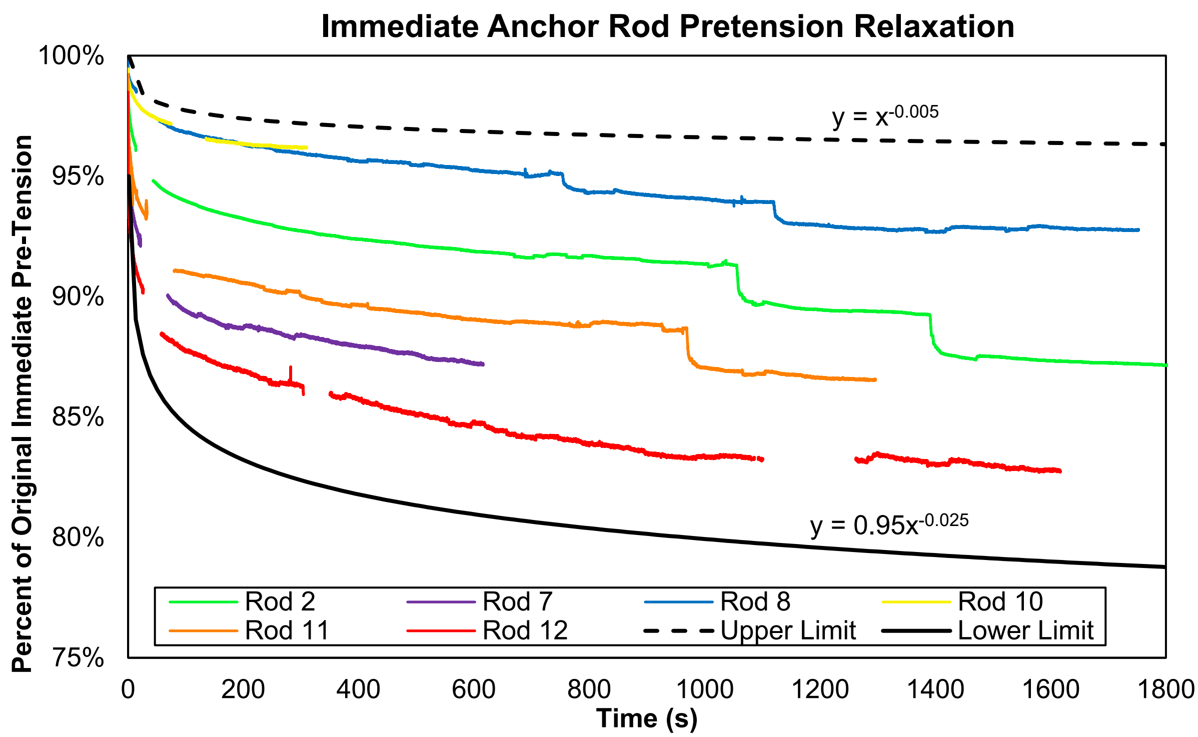


Figure 5.1.11: First 30 Minute Anchor Rod Pretension Loss without Retightening

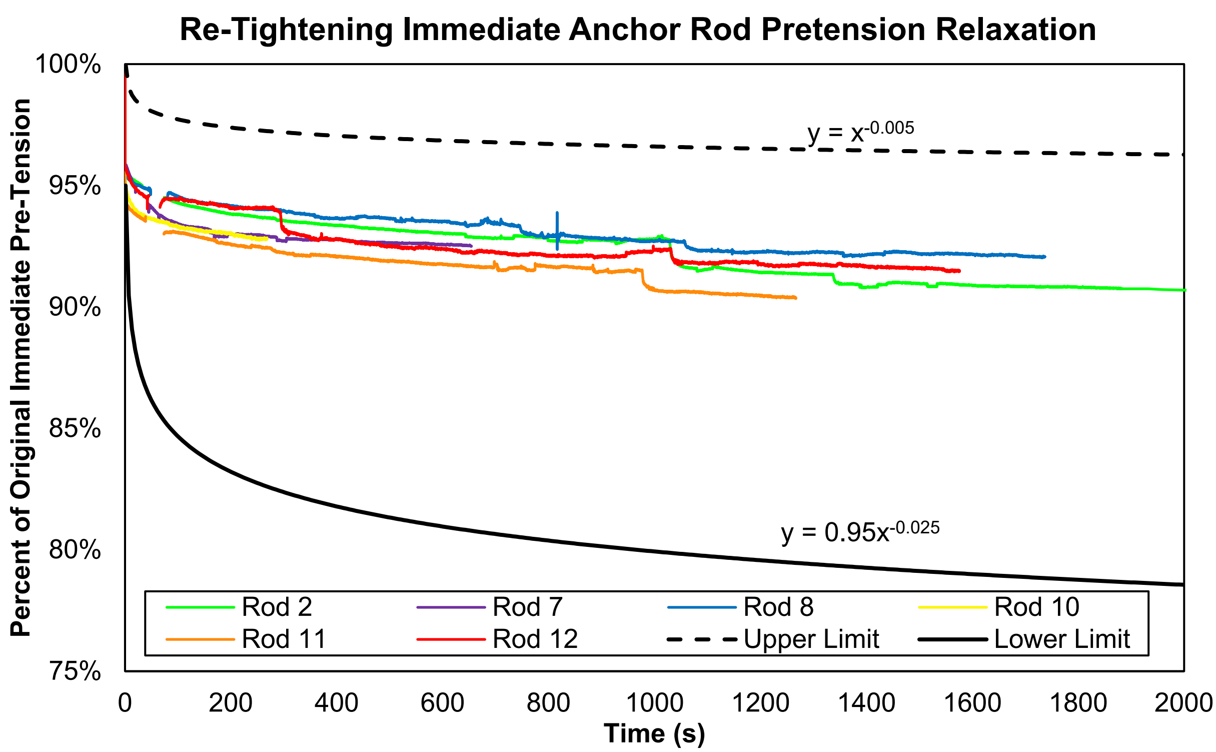


Figure 5.1.12: First 30 minute Anchor Rod Pre-Tension Losses after Retightening

Figure 5.1.14 presents the combined initial and 48 hour relaxation data for the tightened case, but with time on a log scale. Note that the relaxations in this plot will be greater than the 48 hour relaxation presented in Table 5.1.3. The recorded data for Table 5.1.3 is after the initial thirty minute tightening and not immediately after the applied pre-tensioning torque is removed. During the 48 hour relaxation, temperatures in the laboratory varied by around 4 degrees Celsius because the laboratory was opened to allow for other laboratory operations. The temperature differential caused strain increases at the end of the 48 hours. Only data from the non-retightened test are presented because data from the field replicated fatigue test were only collected at 10Hz, which was not sufficient resolution to observe the initial relaxation within 0.1 seconds. Looking into the first minute of Figure 5.1.14 shows that the relative strains exhibit an initial decrease after removal of the torque of about 5% in the first 0.1 to 0.5 of a second, after that, the connections take approximately 60 seconds to 10 minutes to start exhibiting a power-log relationship as modeled in previous literature. The exact mechanism behind this behavior may be a combination of localized plastic yielding, zinc flow from the galvanizing, and creep in the steel, combined with many other aspects. Figures 5.1.13 left and right present roughness that leads to some degree of anchor rod relaxation. If the initial minute to ten minutes of relaxation is alleviated by retightening, the connections likely will perform at a fairly uniform distribution, having approximately 5% initial losses. Recorded losses also approximately align with the observations from directly loosening anchor rods, validating the relaxation approximations. Finally, the 48 hour values recorded in Tables 3.1.2 and 3.1.3 approximately match up, suggesting that after the initial relaxations, pre-tension loss with be fairly uniform, since the pre-tension directly after tightening was not considered as “initial” for the 48 hour losses.

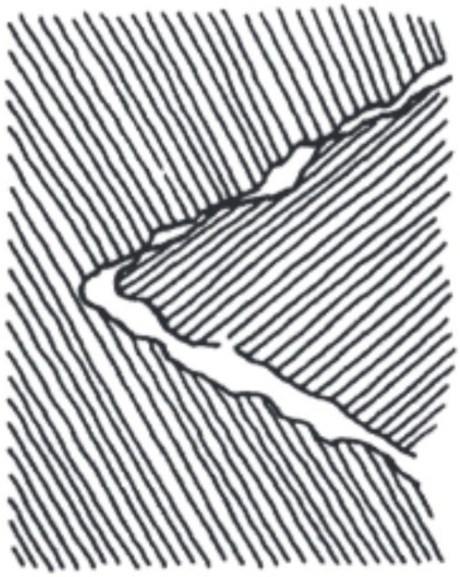


Figure 5.1.13: (Left) Schematic of Thread Roughness from Bickford 1995 and (Right) Roughness on Rod 12 Galvanizing

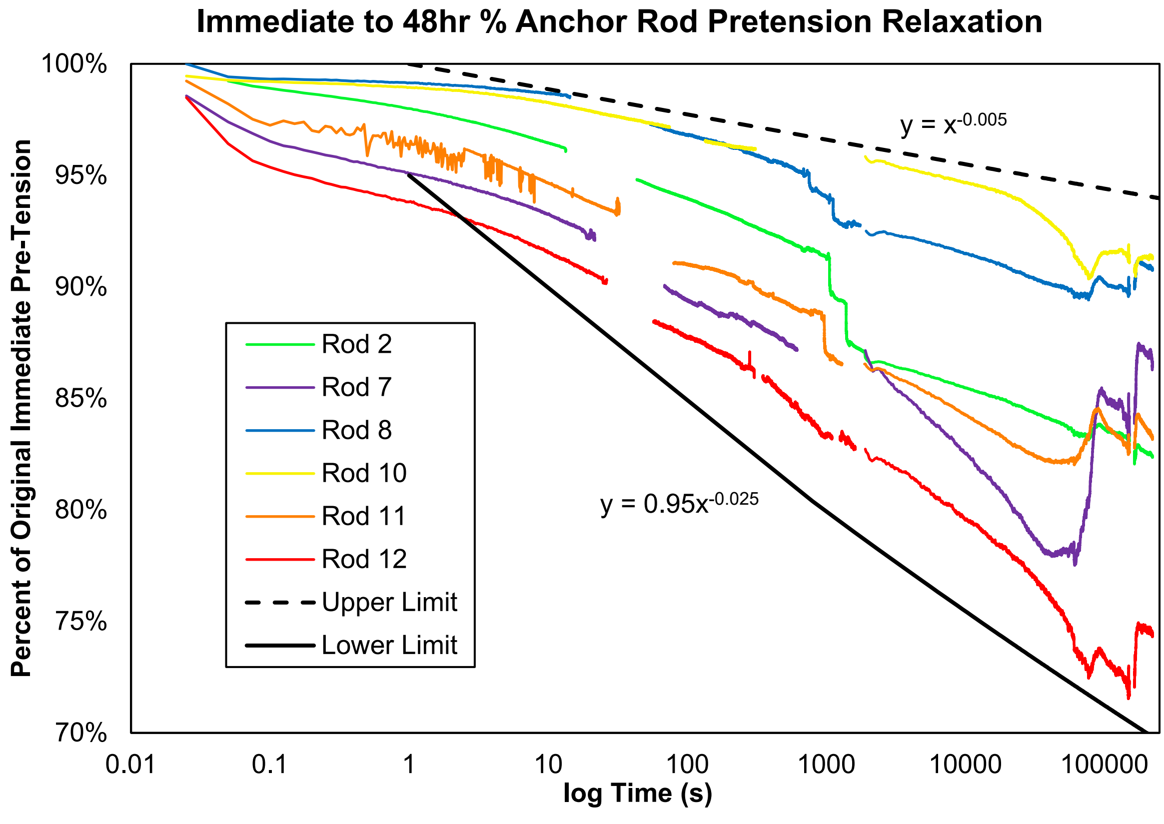


Figure 5.1.14: Full 48 Hour Relaxation

5.2 Tightening Properties

5.2.1 Methodology

Tightening tests focused on torque controlled pre-tensioning on three different anchor rod diameters with five different lubricants. Each lubricant and rod combination was tested 5 times. Three different wrenches were utilized due to various limitations, and to ensure that different torque measurement methods provided consistent results. The first wrench was a HYTORC Stealth 4 with a Vector pump shown in Figure 5.2.1a. Pressure was measured with a Schaevitz 10000 psi hydraulic pressure transducer, which could be correlated to torque through a calibration curve. The second wrench, shown in Figure 5.1.2b was a fixed end socket with 4 foil strain gauges mounted near the base. The calibration curve for this wrench was developed with basic mechanics equations and verified with the other two torque wrenches. Finally, for lower torque measurement, a 100 ft.lb torque transducer was used (Figure 5.2.2). Larger diameter anchor rods, over 1.25” diameter, were tested in a Skidmore-Wilhem Model K bolt tension tester while smaller anchor rods were tested in a Skidmore Wilhelm Model MK. A VTI Instruments EX1629A data collector collected data at a sampling rate of 200Hz for all instruments.

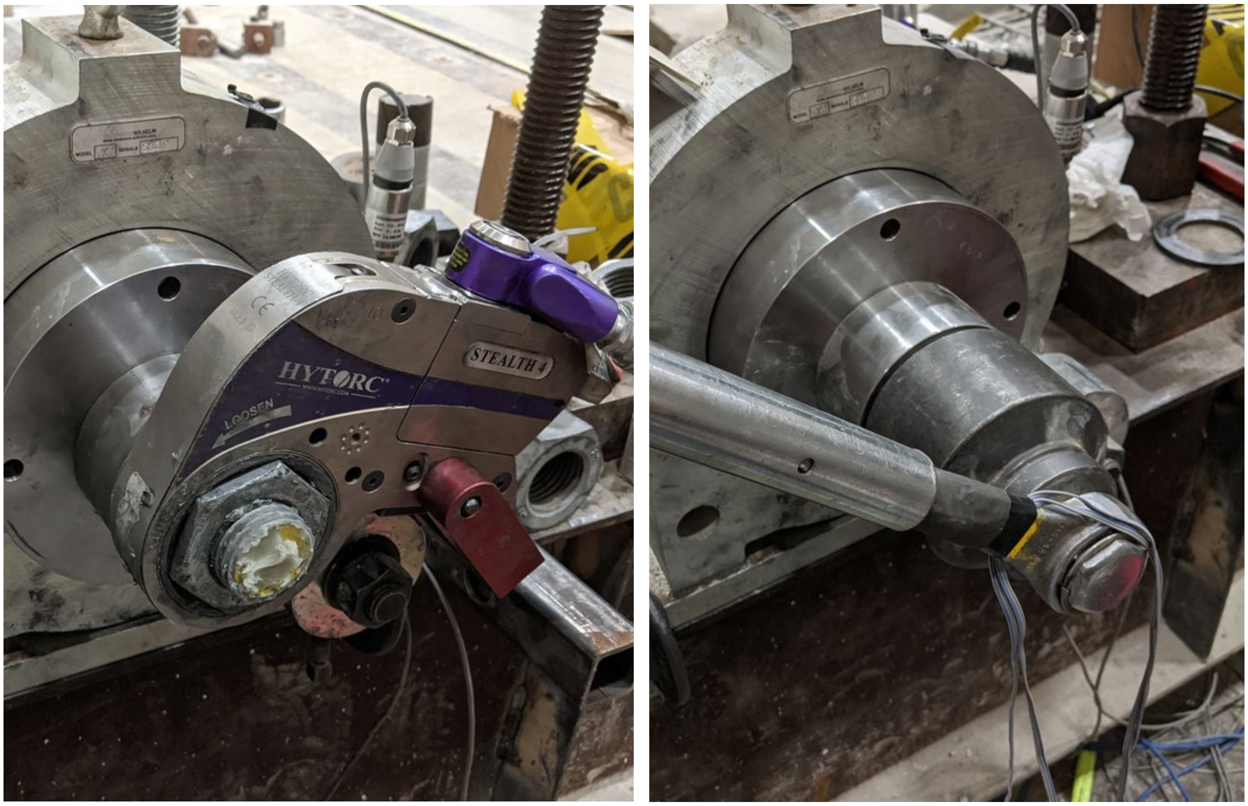


Figure 5.2.1a and b: Skidmore Model K Pre-tensioning with: Hydraulic Wrench; Calibrated Strain Wrench

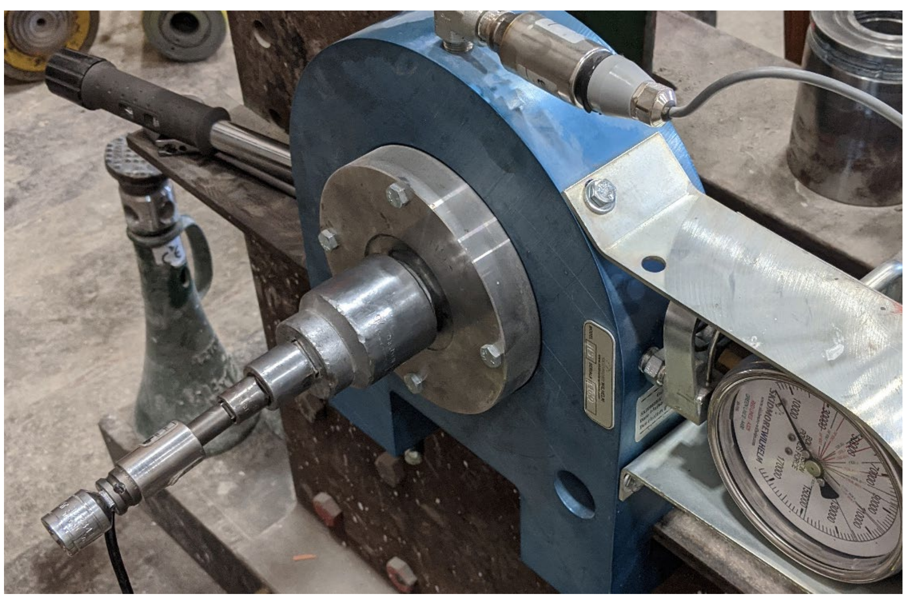


Figure 5.2.2: Pre-tension Testing with Skidmore Model MK and Torque Transducer

5.2.2 Lubrication

The results from the laboratory testing lubrication results are presented in Table 5.2.1, Figure 5.2.3, and Figure 5.2.4. Note that the axis in both figures are in lbs. The x axis is clamp force and the y axis is applied torque divided by the diameter of the tested rod. These data were plotted in this manner so the slope of the trend line would be the nut factor and statistics could be directly performed on the slope. The lubrication impact was tested both for tightening and loosening anchor rods to investigate the possibility of an inspection torque that could be utilized after installation to ease labor concerns. This section refers to Equation 2.1 for torque controlled pre-tensioning, where T is the torque required to be applied to the connection, F is the final clamp or pre-tension force, D is the diameter of the anchor rod, and K is referred to as the nut constant.

$$F = \frac{T}{KD} \tag{2.1}$$

These tightening data mainly illustrate that the current AASHTO code recommended nut factor of 0.12 is likely sufficient for the anti-seize type lubricants on galvanized ASTM F1554 anchor rods. If any of these factors are changed, it would impact the final nut factor and therefore the pretension. In fact, when testing lighter lubricants, like WD 40 and non-lubricated rods, the testing was limited due to the torsional capacities of the Skidmore-Wilhelm tension tester and the double locked nut connection in the back. All of the anti-seize lubricants that were observed in the field, or used by other DOTs preformed approximately the same, averaging out to a nut factor of 0.11, using three different types of wrenches for pre-tensioning. The 95% confidence interval for these laboratory data would result in an error of +/- 4.7 kips of final clamping force using the nut factor of 0.113. Though 0.113 is 8% less than the current specification nut factor, it is recommended that the 0.12 factor is still used. Unlike all prior studies, this nut factor is directly correlated to the instruments, and not manually read, which is impacted by the immediate relaxation. All of the nut factors are laboratory derived, with lubrication thoroughly applied and no environmental variables. Also, as experienced on site, ideal conditions will often not be the case, generally resulting in an increased nut factor. Figure 5.2.3 shows the scatter of these tightening data along with reference nut factors. The nut factors on the graph are purely for reference and are not statistical in nature. Because the hydraulic wrench has a minimum operating pressure, there is an apparent skew at the lower end of the pre-tensioning data. This was investigated with the other two wrenches at lower torques, and, as the torque equation suggests, is due to the operating pressure of the wrench. While this may add uncertainty to the data, it was not removed for transparency and to indicate that there will be greater error when the hydraulic wrench is used at lower torques.

The loosening data resulted in about 80% of the tightening nut factor and generally had a greater standard error, which matches up with literature. (Bickford 1995) For the combined anti-seize lubricants, a loosening k of -0.09 was observed with a 95% confidence interval of +/- 7.8 kips of clamping force. Additionally, the starting point of all of the loosening torques would be impacted by the immediate relaxation of the anchor rods. Figure 5.2.4 shows the distribution of the loosening data points with reference negative nut factors. There is the same lower skew as with the tightening data for lower torques when using a hydraulic wrench for pre-tensioning. Also note that some lubricants, like the wax, have a certain amount of non-linearity at the beginning of the loosening curve. This is likely due to the lubrication properties and the wrench having to overcome the static friction of the connection before loosening. For an inspection torque, the error and relaxation losses will be a crucial factor, to ensure that the inspection procedure verify adequate pre-tension for the connection, but not return excessive false positives. Another important distinction to make is the inspection torque could only tell how much torque was originally applied to the connection; lubrication must also be verified during inspection, for an approximation of the final pretension force.

Table 5.2.1: Summary of Tightening Aspects and Statistics

	Laboratory K	% K uncertainty	Clamp Force Std. Error (kips)	R^2	Laboratory Loosen -K	% K uncertainty	Clamp Force Std. Error (kips)	R^2	Ratio of Loosen to Tighten
Dry*	0.270	0.265%	1.27	0.939	-0.207	-0.389%	-1.85	0.993	-0.766
WD40**	0.212	0.080%	0.14	0.995	-0.163	-0.212%	-0.18	0.972	-0.765
Never Seez	0.120	0.131%	2.49	0.966	-0.097	-0.287%	-5.42	0.946	-0.809
Copper Spray	0.115	0.129%	2.28	0.972	-0.091	-0.324%	-4.52	0.951	-0.795
Wax	0.106	0.105%	2.14	0.984	-0.081	-0.225%	-4.21	0.965	-0.764
Combined:	0.113	0.009%	2.39	0.971	-0.090	-0.197%	3.99	0.966	-0.792

*Did not test on 1.5” due to torsional damage concerns to the skidmore
**Only tested on the 1” diameter rod due to torsional damage concerns to the skidmore

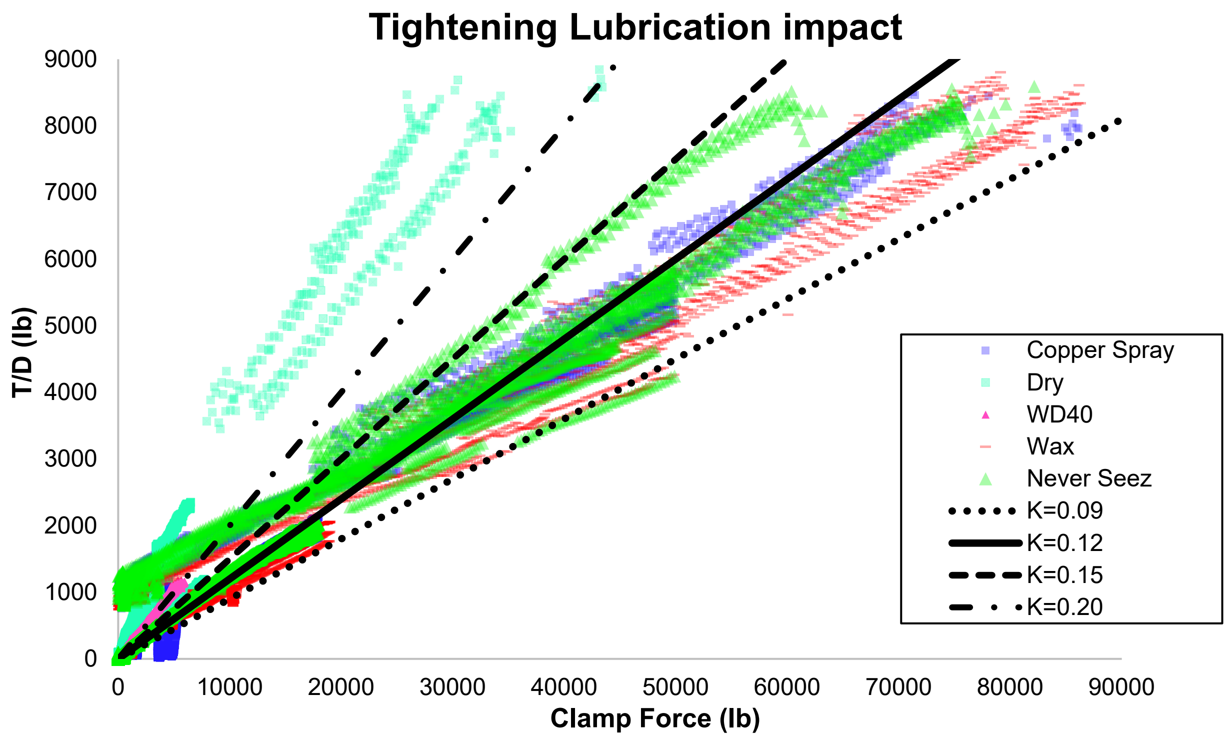


Figure 5.2.3: Tightening Laboratory Tested Properties

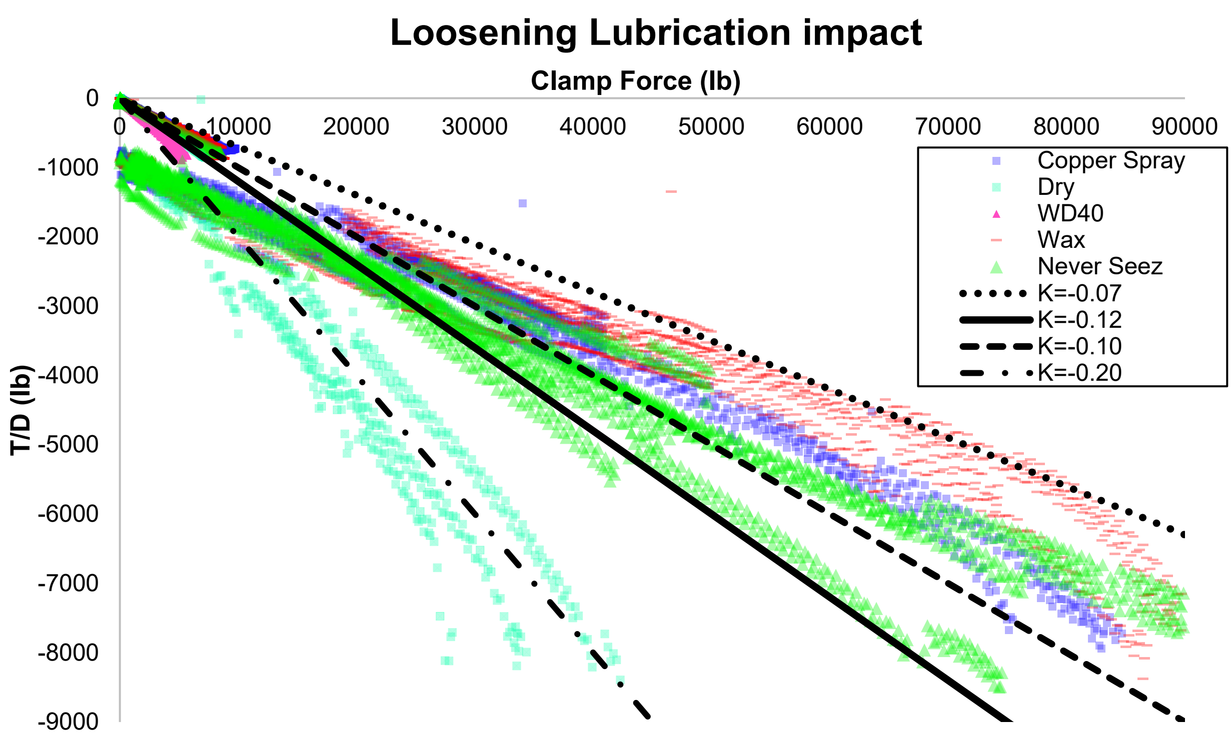


Figure 5.2.3: Loosening Laboratory Tested Properties

5.2.3 Parametric Turn Study

Throughout the course of the study, it became clear that a parametric investigation of anchor rod turn properties would likely have greater efficiency than directly testing the turns in the laboratory.

As discussed in the literature review, joint stiffness is highly dependent on the baseplate and composition of baseplate. A turn and grip length study cannot be accurately replicated with a load cell or bolt tension calibrator because the stiffness distribution of the joint will be in a cylindrical, not frusta shape. Joint stiffness has theoretically no impact on the nut factor in torque controlled pre-tensioning, hence why it is valid in the previously researched case.

To accurately model turn properties for the baseplates on MnDOT's structures, multiple individual plates of galvanized steel at the same thickness of the baseplates would need to be used. A minimum of three anchor rods of each size would need to be instrumented with a bolt strain gauge, calibrated, and fixed on one end, possibly in concrete. For measurements, the turn would need to be continuously measured with inclinometers, string potentiometers, or digital image correlation due to torsional relaxation. Considering the experiences in implementation that turn controlled pre-tensioning is not ideal for many structures due to clearance issues, and that there is a significant amount literature available for turn controlled pre-tensioning, a parametric approach was used for the best value for MnDOT.

Recalling equation 2.2 from the review of anchor rod tightening properties, F is the final pre-tension or clamp force, L is the length of the bolt in the grip length, $\boldsymbol{C}$ is a ratio of bolt stiffness to connection stiffness. E is Young's Modulus, Pi is the pitch (distances between threads i.e. a UNC 6 rod would be 1/6), A is the tensile area of the fastener. Finally, α is the nut turn angle in ratio of a full turn (i.e. 1 is a full turn and 1/6 turn would be 0.1667.

$$F = \frac{C\alpha P_i AE}{L} \tag{2.2}$$

Theoretically, from equation 2.2, as L approaches 0 F should approach infinity and as L approaches infinity, F should approach 0, following a power pattern with L^-1. Naturally, this behavior is critical for SLTS baseplate connections, which are generally ¼" to 3" thick. At these typical thicknesses, the connections are highly sensitive to turn angle and connection stiffness. Additionally, turns in the field can only be accurate to approximately 1/12 of a turn, which even then was difficult to accurately achieve for smaller diameter rods.

Equation 2.2 can be rearranged to Equation 5.1, which is strain based and was used to derive Table 5.2.2. Table 5.2.2 is similar to the ones in RCSC and the Eurocode, based on grip length (L), rod diameter (D), and anchor rod grade. However, Table 5.2.2 is not recommended for use, since the error for the turn values is +100% and -50%. The major limitation with SLTS anchor rods is that they are not being tightened past yield, like structural steel bolts, and that there is a wide variation in structure base designs for SLTS structures. Inherently, turn based pre-tensioning is a displacement based method, which, with small grip lengths, requires a high degree of accuracy. Additionally, snug tight pre-tensions cannot be controlled by turns due to turn non-linearity before the snug tight condition. Since snug tight is the initial condition for turn based pre-tensioning, and the rod is desired to stay in the elastic region, any error in the initial snug tight value will be transferred to the turn of nut. Since turn of nut requires a calibrated torque wrench for the snug tight and verification torque steps, it tends to be somewhat redundant for elastic desired connections.

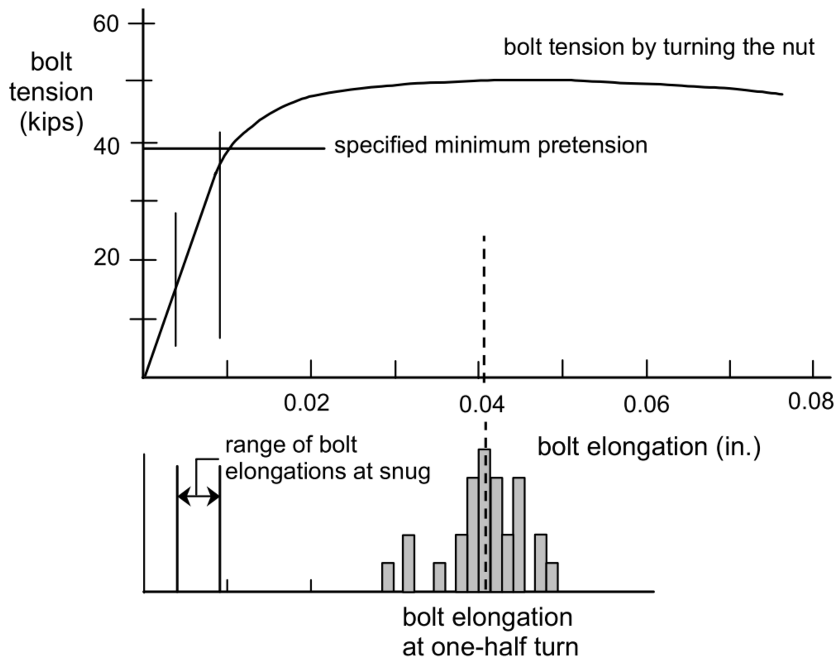
$$\alpha = \frac{\varepsilon L}{P_i C} \tag{5.1}$$

Table 5.2.2: Approximate turns required for anchor rod grades

L/D	Turn required for 0.6Fy after 0.1Fy Snug Tight		
	Gr. 36	**Gr.55**	**Gr.105**
≤1	*	*	1/12
1 to ≤2.5	*	1/12	1/6
2.5 to ≤5	1/12	1/6	1/4
5 to ≤8	1/6	1/4	1/3
8 to ≤11	1/4	1/3	5/12
11≤	Determined by Calculation		

*Displacement controlled pre-tensioning not recommended; 400% error possible

The high degree of accuracy in structural steel connections, as covered in the literature review, is from the yielding of the bolt as outlined in Figure 5.2.4. The elongation procedure from turn of nut works well for structural steel because the bolts are virtually guaranteed to be displaced well into the plastic region, where the tension-turn curve flattens, which is shown in Figure 5.2.4 from Kulak. The bolts being in the plastic region results in minimal final pretension error, approximately +/- 10 to 15%, because the pretension changes minimally with increased turns. Additionally, yielding of structural bolts does not significantly lower the connection pre-tension, which suggests that concerns about yielding anchor rods for loosening may be dubious. The error distribution in Figure 5.2.4 would certainly result in +/-100% pretension error if the bolt was still in the linear region of pre-tensioning. The importance of yielding the connection can also be observed in the allowable error in the RCSC procedures, which is +1/6 and -1/3 turn. This error range could represent the entire AASHTO pre-tensioning specification.



Adapted from Kulak 1983

Figure 5.2.4: Schematic of Structural Steel Bolting Error and Process

To further illustrate the current limitations of AASHTO turn standard, two predicted pretensions for AASHTO base designs can be investigated, both bases are chosen from Table C11.9.3.1-1. (AASHTO 2018) One base will be stiffened with longitudinal attachments and a solid 2” thick baseplate, while the other base will be an 18” stool stiffened base. The following assumptions are considered: anchor rods are 1.5” diameter F1554 Gr. 55, the connection stiffness are approximately the same (0.2), and a 1/3 turn is used (AASHTO Table C15.6.3-1). The 2” baseplate would develop 3100με, 226 kips of pretension force (3.0fy, likely rupturing the anchor rod) and the 18” stool baseplate would develop 344με, 25kips (0.32 Fy) of pretension. This near 1000% difference makes sense because turn controlled pre-tensioning is inherently a displacement controlled method, requiring stiffness to be taken into account, which it currently is not in the AASHTO specification. The possible yielding of anchor rods with the current AASHTO specification was also experienced by Hoisington in research on HMLT structure in Alaska.

Finally, from NCHRP 469, which first proposed the current procedures in AASHTO, torque was disregarded primarily based on research from on structural steel connections along with the fact that James' 1996 study found it to be unreliable. The torque method that was used to assert that torque is unreliable was an un-calibrated 3' pipe wrench attached to a laboratory crane attached to a load cell. In addition, all of the research on tightening properties currently in AASHTO was performed on flat baseplates and did not consider structures with large grip lengths, like with current stool stiffened bases.

5.3 Concluding Points

- **It is likely fatigue loading has relatively little impact on property pre-tensioned anchor rods**. These findings match findings by previous researchers. Additionally, because the fatigue forces on the anchor rods is primarily axial, lock washers for the nut connections would not significantly decrease pretension loss from fatigue.
- **Anchor rods designed with the procedure in AASHTO LRFD SLTS will likely not be the critical details in fatigue**. SLTS structures are usually governed by the post to baseplate connection as observed in testing and by other researchers.

- **For square anchor rod groups with greater than 4 rods, the AASHTO recommended AISC design practice of using a linear strain distribution to determine design forces is likely not valid.** Assuming a linear strain distribution results in underestimations of the applied force to the middle anchor rods and overestimations for corner anchor rods. The observed behavior is likely due to non-uniform baseplate stiffness, resulting in a non-linear strain distribution to the anchor rods. MnDOT may want to reevaluate their design process for determining forces for square anchor rod groups.

- **Leveling nuts are likely to be more critical than the top nuts for loosening**. This is because the anchor rods are acting as a structural member and fastener, instead of just a fastener like structural steel bolts. The increased forces on the grip lengths must be transferred through the leveling nut to the baseplate. There were also large strain increases in the standoff distances of the corner anchor rods when the leveling nuts were brought to a low level of snug tight on the laboratory specimen signpost, suggesting that sufficiently tightening the leveling nuts is critical for installations.

- **Relaxation and creep appears to be the major source of pretension loss in SLTS anchor rods, with possible losses up to 50% of the original pretension if the anchor rods are not retightened**. Retightened anchor rods appear to exhibit a maximum of 25% total lifespan losses. Ninjh's 2016 research on relaxation of structural steel bolts in Europe came to similar conclusions. Hoisington's 2014 research on HMLTs in Alaska also suggested that localized plastic yielding that relaxation occurs from may be a major source of relaxation loss. Research suggests that gross yielding of the anchor rods during initial pre-tensioning does not cause significant pre-strain loss,

- **Retightening the anchor rods significantly decreases the relaxation losses**. Additionally, it is highly likely that the retightening can be applied immediately, approximately after 10 minutes, and will exhibit the same improved relaxation performance as rods retightened 48 hours after installation.

- **For tightening, the current AASHTO nut factor of 0.12 is sufficient and fairly accurate for most anti seize lubricants**. The laboratory testing verified that the nut factor for a variety of anti-seize and wax lubricants matches the values found by Till and Lefke in 1995, which the current AASHTO verification torque is based off of.

- **An installation inspection nut factor of -0.07 could be used to approximately check the pretension in a connection**. This factor would capture almost all error from relaxation and lubricant variation during the original installation.

- **Turn based pre-tensioning is not recommend for connections that are desired to stay in their elastic range.** Accuracy of elastic turn based pre-tensioning is predicated upon accurate snug tight values, which can only be determined by torque, this is also noted by Hoisington and Schaffer. Additionally, the nature of SLTS double nut connections, with large diameter rods and short grip lengths, makes the connections highly sensitive to small variations in turns, which are difficult to control in the field. Creating an elastic, accurate turn specification would also require significant effort, since each connection property and stiffness would need to be directly replicated. A load cell or tension calibrator would have limited use in determining connection stiffness because they do not accurately represent the true connection stiffness.

CHAPTER 6: CONCLUSIONS AND RECOMMENDED CHANGES TO PROCEDURES

6.1 Concluding Statement

After reviewing literature, laboratory testing, results from implementation, and field post monitoring data, it is likely that the problems associated with anchor rod pretension loss arise primarily from the constructability of procedures. A majority of pre-tension loss in SLTS structures that are properly tightened likely occurs from relaxation and not fatigue loading. For connections to retain pre-tension, procedures need to be effective, constructible, and verifiable.

6.2 Limitations

Before covering recommended procedure changes, it is important to consider the limitations of the investigation. Limitations will be presented for the implementation, field monitoring, and lab testing chapters.

6.2.1 Implementation

During implementation, much of the work focused on overhead signs with fewer examples of lighting and traffic signal structures. This could lead to the revised procedures being biased towards ease of installation with overhead signs. In addition, observations made during the implementation were more anecdotal than statistical. For some structures, only one installation or maintenance observation was possible, so the error from different contractors, operators, conditions and other variables were not able to be fully quantified. Finally, procedures were only attempted on MnDOT structure types, so the feasibility may not be universal for all SLTS structures.

6.2.2 Field Monitoring

Much uncertainty with the field monitoring structure arose from the instrumentation and climate conditions. There was no thermocouple used for measuring the temperature at the site, so an approximation was utlized with the temperature from the Minneapolis St Paul Airport. Direct temperature impacts over short time frames were not able to be observed, and the overall data may not directly illustrate theoretical temperature induced stresses. All of the gauges on the signpost were also resistance type strain gauges, so there was added sensitivity if wire resistances differentially changed. The site was next to a roadway, so any snow plowed during the winter would impact the gauges, causing false strain spikes. Conditions also sometimes prevented maintenance of the instruments, so there were periods of the collection that were lost, which may not accurately represent the total loading on the sign post over a year when adjusted for the missed days.

6.2.3 Lab Testing

The major limitation of the lab testing was the fact that fatigue testing was only performed on a single structure and anchor rod type. Extrapolation of the final results may not be accurate for structures that are significantly different in design like light poles or traffic signals. In addition, there is uncertainty in the positioning of embedded anchor rod strain gauges. For the static test results, the stiffness ratios and strains in the grip length may have a high degree of error. Torsional loading was not replicated on the lab base, since the fatigue loading was in line with the base. Torsional loads on the base in the filed could increase the possibility of transverse loosening of the anchor rods, especially in cantilevered overhead signs.

During torque testing, error was mainly due to the bolt tension calibrator measurement limitations. In the bolt tension calibrator, there is a limited torsion force that can be applied to the back locking nuts. Minimal results from unlubricated anchor rods was acquired, due to damage concerns. Stiffness of the instrument and connection also do not directly replicate double nut SLTS connections. Because torque is a force controlled pretension method, the error was somewhat mitigated, but the nut factor may be slightly different in the field. There also was only 5 different lubrication conditions tested, so it is possible that the lab results may not extrapolate to all brands of anti-seize grease or wax lubrication.

6.3 Recommend Changes to Tightening Procedures

6.3.1 Specification Clarity

6.3.1.1 Separation of Overhead Sign and Lighting/Traffic Signal Procedures

Because of the inherent differences in bases of Overhead Signs and Traffic Signal/ Lighting structures, it would likely be beneficial to separate the specifications. Separation of the procedures would increase the clarity of each and be able to focus on some of the more specific aspects of each structure type. In the pre-tensioning steps for Lighting and Traffic Signal structures, the specifications could focus on clearance issues and the quality of torque control. Additionally, the contractors for each type of structure is highly varied, and many lighting structures may be installed by electrical contractor that may not have the same structural experience as an overhead sign contractor.

6.3.1.2 Create Maintenance Procedures

In addition to separating the specifications, it would likely be beneficial to create maintenance procedures for both Overhead Signs and Traffic Signal/Lighting structures. Since maintenance procedures differ greatly from installation, it would likely benefit MnDOT maintenance personnel to have a set of procedures to refer to. Special care also must be taken during maintenance to ensure that the structure remains stable while anchor rods are serviced.

6.3.1.3 Verify Lubrication Areas

With both overhead sign and light pole installations contractors expressed uncertainty concerning the exact areas to lubricate besides anchor rods. Contractors often needed specific instructions on which areas needed to be lubricated on the nuts and washers. The current language in the installation record does not clearly state the surfaces needing lubrication and possibly a graphic should be created illustrating proper lubrication areas.

6.3.1.4 Specify Steps in Logical Manner

Each required step should likely be laid out as an individual torque so steps can be logically followed one at a time without having to go back and forth with half torques. Additionally, it may be beneficial to add descriptions to the steps to explain why they are import to follow for contractors.

6.3.2 Error Control

6.3.2.1 48 Hour Re-tightening Torque

Currently, one of the AASHTO recommended procedures is to retighten connections after 48 hours to 110% of verification torque. This retightening is supposed to account for creep in the galvanizing and minimize initial relaxation losses. The 48 hour retightening was first proposed in NCHRP Report 469 (Dexter and Ricker 2002) without noted references or reasoning for the timeframe. It is suspected that the current specification arose from Fisher's 1973 text that states that: "90% of [the] loss occurs during the first day," and "the relaxation characteristics of assemblies of galvanized plates," and "bolts were found to be twice as great as plain …materials." (Kulak, Fisher and Struik, 1987) The specification also may have been influenced by Yang's 1999 research in galvanized structural bolting relaxation, but is not noted in the references for NCHRP 469.

In practice, the 48 hour retightening torque is likely seldom followed, was not recorded on any of the installation structures, and not used during maintenance due to the resources required. Though the 48 hour retightening is difficult to perform, the concerns about losses are still valid. (Bickford 1997; Fisher and Struik 1974; Yang and Dewolf 1999; Nijgh 2016) Laboratory testing and literature indicated that the retightening torque could likely be applied approximately 10 minutes after the initial tightening with the same relaxation performance improvement.

It is recommended that another pass of the final 100% torque is performed 10 minutes after the initial pre-tensioning. This process should both ensure that the retightening torque is performed and limit the lifespan relaxation losses to approximately 25% to 10% of the applied pre-tension.

6.3.2.2 Lubrication

Throughout implementation, the specified MnDOT bridge grease was generally not used on installations. The majority of lubricants were a sort of anti-seize compound though. Research into literature suggests that the nut factors of many of the used greases is comparable to the specified grease, but verification for specific cases was required. In addition, the AASHTO derived nut factor was found using stick wax by Till and Lefke, which was compared.

In laboratory testing, it was found that most anti seize lubricants have a nut factor of approximately 0.11, which is 8% lower than specified in AASHTO. This is likely because the nut factor derived in AASHTO was manually read off a gauge which would include the 5 to 10% immediate losses, whereas the laboratory tested nut factors were read directly from the instruments by a data collection system. It is recommended that the AASHTO 0.12 nut factor is used though, so immediate relaxation can be automatically accounted for.

6.3.2.3 Specification Simplification

Less steps could likely be used than currently specified. In all of the maintenance and most of the installations, steps were skipped when bringing nuts to snug tight and with the verification torque. The reasoning for the steps is to prevent differential stresses in the bolts, however, doing two steps at snug and two steps at verification may not be proportional enough to cause major differentials in bolt stresses, compared to taking bolts from snug to fully tightened.

Contractors and maintenance workers also expressed that there could be confusion over the "snug tight" term, as many field personnel connoted it to be hand tight, or an approximation.

Changing the specification to four torque steps of: 20%, 60%, 100%, and 100% is recommended. Additionally, a ten minute relaxation period in between the repeated 100% torques would be ideal, though the precise timing could be researched in greater depth to determine a more accurate retightening time frame. Required torque can be calculated with the current equation in AASHTO, shown in Equation 6.1. T is the required torque, F is the desired pretension force, and D is the anchor rod diameter. All applications of pre-tensioning should be applied in a star pattern.

$$T = 0.12FD \tag{6.1}$$

Turn based pre-tensioning is not recommend due to the high sensitivity of elastic displacement controlled pre-tensioning with small grip lengths, accuracy challenges from a constructability standpoint, and variability of base designs. If AASHTO desires to use a turn specification and to keep connections in the elastic region, accurate snug tight values must be defined, since they are the basis for displacement controlled pre-tensioning. Additionally, grip length and connection stiffness must be taken into account.

For some conditions, particularly in maintenance, a turn specification may be the only option. In this case, it is recommended that snug tight be specified as 0.1Fy, as recommended from the previous study (Chen 2018) and require a calibrated torque wrench be used to achieve it. The nut factor must be adjusted accordingly from literature for structures installed or maintained without lubricant or an anti-seize type of grease.

6.3.2.4 Existing HMLT Installation and Maintenance

With the revised design clearances, the HYTORC low profile stealth series hydraulic torque wrench should work on new HMLT installations. The wrench was very close to fitting on the newer base design at the Maple Grove site (A14E 4). With the stack socket attachment, the wrench nearly worked on the older base design and was far easier to place. Contractors may want to consider using the stack socket attachment during installations for easier placement and removal of the hydraulic torque wrench.

On in place HMLT structures though, the only feasible retightening option is likely a slugging type wrench, since both hydraulic wrench options encountered significant difficulties. For in place retightening procedures on MnDOT HMLTs, an approximate turn procedure will need to be used. From Table 5.2.2, a 1/6 turn or refusal from a slugging wrench, whichever comes first, is recommended for the legacy design structures. The required snug tight force is 26.25kips, which corresponds to a snugging torque of 1100 ft.lbs if the anchor rods are unlubricated, using an approximate nut factor of 0.25. This may be able to be achieved with a 6' cheater bar attachment to an open ended wrench, since the average person can apply 200 lbs of force without slipping in the field. There will naturally be a high degree of error with this method, but for maintenance of these particular existing structures it is likely the most feasible option. The force required to rupture the anchor rods is not achievable manually, so anchor rods will not be in danger of failing with this method.

6.3.2.5 Pre-Tensioning With Direct Tension Indicators

If a calibrated wrench is not used for pre-tensioning, DTIs are recommended for the installation. DTIs will also likely result in higher pretension accuracy than torque controlled pre-tensioning, since they directly measure the clamping force in a connection. They also enable inspection after installation, since the DTI gap can be measured with a feeler gauge. However, DTIs may require more skill during installation to correctly check if the gap is adequate and may be difficult to observe in enclosed bases. The relaxation of connections with DTIs has been researched structural bolts with inconclusive results. (Reuther, et al. 2014) These findings may not extrapolate well to anchor rods with galvanized DTIs and more research needs to be pursued on the subject. Additionally, since the DTIs are plastically deformed, they cannot indicate pre-tension loss or relaxation.

Any installations using DTIs should adhere to ASTM F2437, Style 2 and either Grade 55 or 105. For this specification, the DTIs are calibrated to 60% of the rod yield strength. It is also permitted to pretension to a different force, if desired, but the DTI gap must be calibrated with a bolt tension calibrator. (ASTM, 2019) AASHTO and manufacturers recommend that DTI washers be used on the top of the leveling nuts so that the complete clamping force in the connection can be measured and to further prevent the nut from turning on the DTI. If the structure was being pre-tensioned from the leveling nuts, the opposite would be true and the DTI would be placed under the top nut.

6.3.3 Quantifiable Verification

In interviews and during site inspections, MnDOT inspectors noted that it would be helpful to have an inspection method after installation, since observing every structure installation is burdensome on resources.

If DTIs are not used for installation, torque supplemented with a check for lubricant type could be substituted to approximate a minimum pretension in the anchor rods. While this is an approximation, it could ensure that the connections were pre-tensioning to approximately the correct value. A negative, or loosening nut factor of 0.7 is recommended for an inspection torque determined by Equation 6.2. The 0.7 nut factor was simplified to half of the installation torque to account for relaxation and the error covered in the tightening section, so it is outside of the 95% confidence interval for all loosing torques.

$$T_{insp} = 0.5T \tag{6.1}$$

For the inspection torque to be valid, lubrication type also must be verified during the inspection, so the nut factor is consistent. If the nut on a pre-tensioned connection turns off with the prescribed inspection torque, it is highly probable that the connection was under pre-tensioned during the installation.

One of the downsides to inspecting connections after installation is that exact following of the procedure cannot be checked, such as: tightening in a star pattern, thorough lubrication, tightening the leveling nuts, and proper number of steps. This may result in greater error in the final pretensions, however, the savings of inspection after installation may justify the limitations.

6.4 Further Investigation Recommendations

As with many testing regimens, more questions were raised throughout the testing and data processing journey. Below are a few recommended areas for investigation that could be pursued to further improve the performance of double nut connections on SLTS structures.

- **Implementation of DTI pre-tensioning in the field**: During this study, installation of structures using DTI washers was not observed. Accurate measurement of the DTI gap is required for both installation and inspection. With the enclosed bases on many SLTS structures and overhangs covering the leveling nuts, proper installation with DTIs will likely require trial and error in the field to develop an adequate procedure for all structures.

- **Implementation of the revised procedures in the field**: The current revised torque procedures developed from implementation and lab testing are fairly likely to work, however, there is still uncertainty with a couple structure types. In particular, structures with grade 105 anchor rods in enclosed bases present an issue. For HMLTs or large light post bases, the installation pre-tensioning procedures were not attempted.

- **Field Monitoring on Light Posts:** Connections in light posts theoretically have the greatest risk of pretension loss due to their low diameter to grip length ratio. It would likely be beneficial to instrument a light post in the field to monitor the dynamic forces on the anchor rods.

- **Relaxation Loss of Connections**: Further studies could compare the relaxation of different sized connections with retightening torques applied at different time periods after tightening. The impact of DTI washers and surface coatings could be investigated to better quantify the time for the application of retightening torque. Statistics of the relaxations could also be used to estimate final pretension values better.

- **Force Distribution of Square Anchor Rod Groups with greater than 4 rods** Laboratory testing indicated that the linear strain distribution used to estimate design forces significantly underestimates forces in center anchor rods for square anchor rod groups. Because this effect is impacted by the stiffness of the baseplate, MnDOT may want to reevaluate their design procedures, lengthen the corner pole to base plate stiffeners, or change to a circular anchor rod group in to approximately ensure a uniform baseplate stiffness.

- **Development of an F-S-N curve under AASHTO load levels for a fatigue service limit state**: An estimation of the 60% Fy pre-tension loss occurring under typical AASHTO fatigue levels applied to the standoff distance could be investigated in the laboratory with fairly traditional fatigue testing methods. Development of a design curve for pre-tension loss estimation over the life of a structure could be beneficial for design. Future structures could be designed considering the service fatigue pre-tension losses, referencing the applied pretension, the standoff distance stresses, and stress cycle counts.

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APPENDIX A: RECOMMENDED CHANGES TO AASHTO LRFD-SLTS C15.6.3

15.6.3—Anchor Bolt Tightening

All anchor bolts shall be adequately tightened to prevent loosening of nuts and to reduce the susceptibility to fatigue damage. Anchor bolts in double-nut connections shall be pretensioned. Anchor bolts in single-nut connections shall be tightened to at least one half of the pretensioned condition. Anchor preload shall not be considered in design.

C15.6.3

The fatigue strength of anchor bolt connections is directly influenced by several installation conditions. Most important, all anchor bolt nuts shall be adequately tightened to eliminate the possibility of nuts becoming loose under service load conditions. When nuts become loose, the anchor bolts are more susceptible to fatigue damage. Force controlled pretensioning with a calibrated wrench or Direct Tensile Indicating washer is recommended for SLTS structure anchor bolts. Displacement based turn of nut pretensioning is not recommended for SLTS anchor bolts because there is a high degree of final pretension error due to short grip lengths typical of SLTS structures. ~~The most common method of pretensioning anchor bolts is the turn-of-nut method. Top nut rotation requirements to achieve proper anchor bolt pretensioning are given in Table C15.6.3-1. For single-nut connections, one half of the pretensioned condition may be estimated as 50 percent of the values for the turn-of-nut method and can be estimated by knowing the length of anchor bolt between the top of the foundation and the bottom of the top nut. The elongation that produces one-half of the yield load on the anchor bolt over this length is calculated. The required number of nut turns is then determined using the calculated elongation and the anchor bolt thread pitch.~~

~~**Table C15.6.3-1—Top-Nut Rotation for Turn-of-Nut Pretensioning of Double-Nut Moment Connections**~~

~~Anchor Bolt~~	~~Nut Rotation beyond Snug-Tight[a,b,c]~~	
~~Diameter, in.~~	~~F1554 Grade 36~~	~~F1554 Grades 55 and 105, A449, A615, and A706 Grade 60~~
~~$\le 1^1/_2$~~	~~$^1/_6$ turn~~	~~$^1/_3$ turn~~
~~$> 1^1/_2$~~	~~$^1/_{12}$ turn~~	~~$^1/_6$ turn~~

~~[a] Nut rotation is relative to anchor bolt. The tolerance is plus 20 degrees ($^1/_{18}$ turn).~~

~~[b] Applicable only to double-nut moment connections.~~

~~[c] Use a beveled washer if the nut is not in firm contact with the base plate or if the outer face of the base plate is sloped more than 1:40.~~

Anchor bolt preload does not affect the ultimate strength of a connection, but it does improve connection performance at working load levels. Fuchs et al. (1995) state that anchor bolt preload will affect the behavior of the anchor bolt at service loads and has practically no influence at failure load levels.

The testing described in NCHRP Report No. 412 (Kaczinski et al., 1998) shows that the Constant Amplitude Fatigue Threshold (CAFT) for anchor bolts is nearly the same for both snug and pretensioned installations. (In previous editions of this specification, the CAFT was termed Constant Amplitude Fatigue Limit, CAFL). Therefore, snug-tightened and pretensioned anchor bolts are designed for strength and fatigue in the same manner. Whenever practical, however, anchor bolts should be pretensioned. Although no benefit is considered when designing pretensioned anchor bolts for infinite life, it should be noted that the pretensioned condition reduces the possibility of anchor bolt nuts becoming loose under service-load conditions. As a result, the pretensioned condition is inherently better with respect to the performance of anchor bolts.

The following procedure adapted from ~~Garlich and Thorkildsen (2005)~~ should be considered when pretensioning double-nut moment connections. It has been derived from numerous references, including Till and Lefke (1994), James et al. (1997), Johns and Dexter (1998), and Dexter and Ricker (2002), Garlich and Thorkildsen (2005).

1. Verify that the nuts can be turned onto the bolts past the elevation corresponding to the bottom of each in-place leveling nut and be backed off by the effort of one person using a 12-in. long wrench or equivalent (i.e., without employing a pipe extension on the wrench handle).

2. Clean and lubricate the exposed threads of all anchor bolts, ~~and~~ leveling nuts, and the outward faces of washers. Re-lubricate the exposed threads of the anchor bolts and the threads of the leveling nuts if more than 24 hours has elapsed since earlier lubrication, or if the anchor bolts and leveling nuts have become wet since they were first lubricated. Lubrication should be an anti seize grease or wax type.

3. Turn the leveling nuts onto the anchor bolts and align the nuts to the same elevation. Place structural washers on top of the leveling nuts (one washer corresponding to each anchor bolt).

4. Install the base plate atop the structural washers that are atop the leveling nuts, place structural washers on top of the base plate (one washer corresponding to each anchor bolt), and turn the top nuts onto the anchor bolts.

5. Bring all nuts to hand tight.

6. ~~Tighten top nuts to a snug-tight condition in a star pattern. Snug-tight is defined as the maximum nut rotation resulting from the full effort of one person using a 12-in. long wrench or equivalent~~. Tighten the leveling nuts in a star pattern to approximately 0.15 T_v. A star tightening pattern is one in which the nuts on opposite or near-opposite sides of the anchor bolt circle are successively tightened in a pattern resembling a star. (e.g., For an 8-bolt circle with anchor bolts sequentially numbered 1 to 8, tighten nuts in the following bolt order: 1, 5, 7, 3, 8, 4,
6, 2.)

~~7. Tighten leveling nuts to the snug tight condition in a star pattern.~~

Tighten the top nuts to the verification torque, T_v shown in the equation below. Top nuts should be tightened in three steps of 0.2 T_v, 0.6 T_v, and 1.0 T_v. Each tightening step should be completed in a star pattern.

~~Before final tightening of the top nuts, mark the reference position of each top nut in a snug-tight condition with a suitable marking on one flat with~~

~~corresponding reference mark on the base plate at each bolt. Then incrementally turn the top nuts using a star pattern until achieving the required nut rotation specified in Table C15.6.3-1. Turn the nuts in at least two full tightening cycles (passes). After tightening, verify the nut rotation. Using a torque wrench, the verification torque, computed as shown below, should be applied to the top nuts. Inability to achieve the verification torque may indicate thread stripping.~~

$$T_v = 0.12 d_b F_t$$

where:

T_v = verification torque
d_b = nominal bolt diameter (in.)
F_t = installation pretension (kips)
($F_t = 0.5F_y$ for Grade 36 bolts and $0.6\ F_y$ for other bolts)

8. Retightening of installation by use of torque is recommended ~~48 hours~~ 10 minutes after bolt tightening to account for any creep in the galvanizing within the threads.The retightening torque is 100 percent of the verification torque.

Direct-tension-indicating (DTI) washers provide a means of verifying that the anchor bolt preload is achieved. Direct-tension indicators for anchor bolts in diameters up to $2^1/_2$ in. and other applications are covered by ASTM F2437. Specifications include DTIs for Grade 55 and Grade 105 anchor bolts with preload of 60 percent of the yield strength. Use of DTIs with oversize base plate holes may require plate washers in addition to the hardened washers. It is recommended that DTIs be placed between the leveling nut and base plate to assure that the top nuts are fully tensioned to the base plate.

APPENDIX B: RECOMMENDED CHANGES TO MNDOT CONSTRUCTION SPECIFICATIONS

2545.3

H.2.b Double-Nut Anchor Rod Connections

Poles requiring double-nut connections use two heavy hex nuts for each anchor rod to fasten the base plate to the foundation anchor rods. A bottom nut, also called a leveling nut is positioned under the base plate to level and support the pole and a top nut is located above the base plate.

Two hardened flat washers are required for each connection. Place one washer directly above the leveling nut and the other washer directly under the top nut. Use additional washers or spacers if required by the pole manufacturer.

For poles designed to be installed using a double-nut anchor rod connection use the standoff distances provided by the distance of less than 1 in if the anchor rod diameter is greater than or equal to 1 in. For anchor rods with a diameter less than 1 in, use a standoff distance of less than one anchor rod diameter.

Fully tighten the connections in accordance with the pole manufacturer's installation instructions. If the pole manufacturer does not provide anchor rod connection tightening methods or refers to MnDOT Specifications for final tightening, tighten the connections in accordance with the following:

Tightening may be performed with a calibrated wrench or Direct Tensile Indicators (DTIs). Turn based tightening is not permitted without permission of the Engineer.

Tighten each connection to 60% of the anchor rod yield strength meeting the requirements of ASTM F1554.

~~After snug tight condition has been met for top nuts and leveling nuts, fully tighten the anchor rod connections by turning the leveling nuts to the required rotation specified in Table 2545-1:~~

~~Table 2545-1~~ ~~Leveling Nut Rotation for Tightening Double-Nut Anchor Rod Connection~~	
~~Anchor Rod Diameter, in~~	~~Nut Rotation beyond Snug-Tight~~
~~≤ 1 ½~~	~~1/6 turn~~
~~> 1 ½~~	~~1/12 turn~~
~~* Before turning the leveling nuts to the required rotation, mark the top of the foundation showing the before and after rotation positions of each leveling nut. Incrementally turn the leveling nuts using a crisscross or star pattern until the required nut rotation shown in this table has been achieved. Turn the nuts in at least two full tightening passes. Verify the nut rotation after tightening.~~	

H.2.b(1) Calibrated Wrench Tightening

The following procedure should be used when tightening connections with a calibrated wrench:

(1) Wrench Calibration shall have been performed within one (1) year of the installation.
(2) After placement of the pole, bring all nuts to hand tight.
(3) Tighten leveling nuts with an open ended wrench corresponding to the length in Table 2545-1 using a smooth tightening motion.
(4) Tighten the top nuts to 20% of the torque in Table 2545-2 with a calibrated wrench in a crisscross or star pattern.
(5) Tighten the top nuts to 60% of the torque in Table 2545-2 with a calibrated wrench in a crisscross or star pattern.
(6) Tighten the top nuts to the torque in Table 2545-2 with a calibrated wrench in a crisscross or star pattern.
(7) Allow for 10 minutes of anchor rod relaxation.
(8) Tighten the top nuts to the torque in Table 2545-2 with the calibrated wrench in a crisscross or star pattern.

Table 2545-1 Open Ended Wrench Lengths for Tightening Leveling Nuts				
Anchor Rod Diameter, (in)	Anchor Gr. (Yield Stress)			
	36	55	105	
3/4	1			Open Ended Wrench Length, (ft)
1				
1.25				
1.5	1	1	2	
1.75	1	1.5	3	
2	1.5	2	4	
2.25	2	3.5	6	
2.5	3	4.5	8	

*The open ended wrench is not required to be the exact length prescribed in this table and can be held at the required distance from the leveling nut.

Table 2545-2 Required Torque for Calibrated Wrench Tightening				
Anchor Rod Diameter, in	Type A F1554 Gr. 36	Type B F1554 Gr. 55	Type C F1554 Gr. 105	Type D A276
	Required Torque, ft.lbs			
3/4	55	83	158	64
1	131	200	382	153
1 1/4	262	400	764	306
1 1/2	456	696	1328	532
1 3/4	719	1098	2095	838
2	1080	1650	3150	1260
2 1/4	1580	2414	4607	1843
2 1/2	2160	3300	6300	2520

*Torques are calculated using the verification torque equation in AASHTO LRFD-SLTS: C15.6.3.
**ASTM A325 and 490 bolts shall be tightened with the procedures outlined in MnDOT Specification 2402.3

H.2.b(2) Direct Tension Indicator (DTI) Tightening

Installation with DTIs shall conform to ASTM F2437 and manufacturer specifications excluding the following:

(1) DTIs should be mocked up on the anchor rods prior to tightening in order to ensure that proper gap measurement can take place.

(2) Type A (F1554 Gr.36) and Type D (A276) installations require the DTI gap to be calibrated with a bolt tension calibrator to avoid exceeding 60% of the rod yield strength. A F2437 Gr.55 DTI is required for Type A and D installations.

(3) Where possible, install the DTI washer opposite to the turned nut. In general, this will be the leveling nut.

(4) Always have DTI protrusions facing away from the base and use a hardened washer to separate the nut from the DTI.

H.2.b(3) Inspection Procedure for Calibrated Wrench

It is preferred that the Engineer, or Engineer's representative, is present for the tightening of any anchor rods. In the event that the Engineer is not present for the tightening, inspection of the anchor rods can be achieved by applying ½ of the tightening torque in Table 2545-2 in the opposite direction of tightening with the following steps:

(1) Lubrication should be verified as the MnDOT approved bridge grease, or an equivalent approved anti-seize type of lubrication.
(2) Nuts and anchor rods should be marked with a reference line before attempted loosening.
(3) If greater than 2 or 50%, whichever comes first, of nuts on a structure indicate loosening during inspection with the reverse torque, all anchor rod connections should be retightened.
(4) If nuts do not show loosening during inspection, apply the required torque from Table 2545-2 in the tightening direction on nuts that were inspected.

C~~heck for loose nuts 48 h – 96 h after tightening anchor rod connections. If nuts move, re-tighten the connection turning the nut to the required rotation specified in Table 2545-1. If more than half of the anchor rod connections nuts move per pole, remove the pole and disassemble the connections. Re-install the pole and connections.~~

Install rodent intrusion barrier in accordance with 2545.3W.