An Investigation of Nut Loosening and Review of Tightening Procedures for Anchor Rods in Highway Ancillary Structures

Japsimran Singh

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Civil Engineering

Matthew H. Hebdon, Chair

Thomas M. Murray

Matthew R. Eatherton

Ryan J. Sherman

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Abstract

Ancillary structures are highway support structures such as traffic signals, sign structures, luminaires, and high-mast light towers which are typically fastened to a concrete foundation using embedded anchor rods and anchor nuts. The inventory of ancillary structures across the United States is huge, and these structures vary dramatically in type, age, size, and material. There have been reported cases of anchor nut loosening on ancillary structures in the past few decades, but the cause of loosening is still unknown. Ancillary structures are susceptible to vibrations due to different wind loadings like natural gusts, vortex shedding, galloping, and truck-induced gusts. Wind-induced vibrations are believed to be one of the potential causes of anchor nut loosening. Previous research also suggests that vibrations can lead to loosening of nuts in structural and mechanical connections. There is concern regarding the current tightening procedures specified in the various federal and state specifications. Improper tightening can potentially lead to anchor nut loosening under the effect of wind-induced vibrations. In ancillary structures, the anchor rods and nuts are first snug-tightened using a wrench before fully pretensioning them as per the current specifications. The snug-tight condition is vaguely defined at present and needs revisions to avoid any under-tightening or over-tightening. Galvanization and overtapping of the anchor nuts also pose a potential concern. Anchor nuts are tapped oversize after galvanization to ensure the nuts fit well on the galvanized rod. American Society for Testing and Materials (ASTM) standards provide specific allowable tolerances on the thread parameters of the anchor rod and nut after galvanization and overtapping. Any deviation from the allowable tolerances can lead to gaps between the mating threads, which can contribute to the loosening of nuts under vibrations.

This study focuses on investigating the following potential causes of loosening: improper tightening, wind-induced vibrations, snug-tight condition, and thread fabrication tolerance. Current tightening procedures for double-nut and single-nut connections on ancillary structures were verified using a tightening study as part of the investigation. New revisions to the specified nut rotation values for double-nut connections and a draft for proposed new specifications on single-nut connections has been provided as a result of discrepancies and inconsistencies in the current specifications. Vibration testing of a full-scale traffic signal was conducted on the basis of results from a four-month field monitoring program in order to investigate the effects of wind-induced vibrations on anchor nut loosening. It was concluded from testing that improper tightening (pretension < 5ksi) can lead to loosening of anchor nuts under wind-induced vibrations. A small-scale testing was also conducted to verify the results from the large-scale vibration testing. Snug-tight pretension in grade 55, 1-inch and 2-inch anchor rods was found to be highly variable due to different wrench lengths and personnel strength. Thread parameters of galvanized anchor rods and nuts procured from 3 different regional suppliers were found to be within specified tolerances. Various recommendations were then made as a result of the above tightening, vibration, and thread tolerance studies in an effort to reduce the cases related to anchor nut loosening in the future.

An Investigation of Nut Loosening and Review of Tightening Procedures for Anchor Rods in Highway Ancillary Structures

Japsimran Singh

General Audience Abstract

Ancillary structures like traffic signals, sign structures, and light poles are typically connected to the ground using anchor rods and anchor nuts. There is a very large number of ancillary structures throughout the United States and vary in type, age, size, and material. There have been reported cases of anchor nut loosening on ancillary structures in the past few decades, but the cause of loosening is still unknown. Different types of wind loadings like natural gusts, vortex shedding, galloping, and truck-induced gusts vibrate the ancillary structures. These vibrations due to the wind are believed to be one of the potential causes of anchor nut loosening. Vibrations in the past have been shown to cause loosening of nuts in other structural and mechanical connections. There is also concern that the anchor rods and anchor nuts are not tightened properly as per the specifications, which can lead to loosening of nuts when the ancillary structures vibrate due to wind loadings. In ancillary structures, the anchor nuts are first made tight using a wrench with the full effort of a worker, also known as the snug-tight condition. The snug-tight condition is not properly defined at present and needs to be changed to prevent any under-tightening or over-tightening of the anchor nuts. Also, the anchor rods and nuts are generally coated with a hot zinc layer to prevent their corrosion when exposed to environmental effects like ice, snow, humidity, and rain. This process is called galvanization. The American Society for Testing and Materials (ASTM) provides some guidelines on the amount of coating allowed on the threads of the anchor rods and nuts. Any deviation from the allowable tolerances can lead to gaps between the threads of the anchor rod and nut, which can contribute to the loosening of nuts during vibrations of ancillary structures due to wind.

This study focuses on investigating the following potential causes of loosening: improper tightening, vibrations of ancillary structures due to wind, snug-tight condition, and allowable tolerances for the amount of galvanization. Current tightening procedures for anchor rods and nut on ancillary structures were verified using a tightening study as part of the investigation. New revisions to the current tightening procedures have been provided as a result of discrepancies and inconsistencies observed in the current specifications. A traffic signal and a light pole were instrumented with sensors for four months to measure wind-related forces acting on these structures. Further, a full-scale traffic signal was vibrated in the laboratory using an electric motor to simulate the vibrations due to the measured wind forces. It was determined from the testing that if the anchor nuts were not properly tightened, they could become loose during vibrations due to wind. A small-scale testing was also conducted to check the results from the full-scale vibration testing. The snug-tight force in the anchor rods was also found to be dependent on the length of the wrench and the worker tightening it. The amount of galvanization on the rods and nuts procured from 3 different suppliers were found to be within allowable tolerances. Various recommendations were then made as a result of the conclusions in an effort to reduce the cases related to anchor nut loosening in the future.

To my parents, Sarv Deep Singh and Chanmeet Kaur, and to my girlfriend, Eshwari without whom I never would have completed this journey. This one is for you.

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CHAPTER 1: Introduction

1.1 Motivation and Overview

Anchorage assemblies, consisting of anchor rods and nuts, are used to securely fasten ancillary structures to a foundation. Ancillary highway support structures include overhead sign structures, traffic signals, luminaires, and high-mast lighting towers (HMLTs). Ancillary structures vary widely in type, material, size, and age, and typically have either a single or double nut connection at the structure's foundation. In the past, there have been incidents where ancillary structures have failed, resulting in the structure falling onto roadways. Two of these incidents occurred in 2012, when a cantilever sign structure collapsed in Prince George County, Virginia, and another cantilever sign structure collapsed in Fairfax, Virginia. While heavy windstorms were occurring in the area during both incidents, a prior inspection of each of the structures confirmed that the anchor nuts were loose on both structures, and it was these loose nuts that were believed to be partially responsible for both failures. Following these events, a quality assurance inspection was conducted by the Virginia Department of Transportation (VDOT), and 30% of cantilevered overhead structures throughout the state were found to have loose anchor nuts.

There have been reported cases of loose anchor nuts on ancillary structures during field inspections across the United States (Garlich and Koonce 2010). Anchor nuts have been found loose on different types of ancillary structures: HMLTs (Hamel and Hoisington 2014; Sherman 2009) and cantilever support structures (Till 1992). Anchor nuts, if loose, can lead to higher stresses in the anchor rods and further contribute to a structure's collapse; therefore, anchor nut loosening poses a large safety and liability risk to the public and the Department of Transportation.

While the exact cause of loosening of anchor nuts is unknown, potential causes are thought to range from improper tightening, to wind-induced vibrations, to overtapping of the nuts.

Currently, turn-of-the-nut tightening procedures, as specified in the American Association of State Highway and Transportation Officials (AASHTO) specifications (AASHTO 2015), and Virginia Department of Transportation (VDOT) implementation documents (VDOT 2016a), are required for fastening the anchor rods on ancillary structures. The tightening procedures have been adapted from Federal Highway Administration (FHWA) tightening guidelines (Garlich and Thorkildsen 2005). The tightening specifications first require that the top and bottom anchor nuts are snug-tightened, and then the top anchor nut is tightened in angular increments up to a specific rotation based on the diameter and grade of the rod. Upon review, there are two areas that are overlooked in the tightening specifications. First, the snug-tight condition is vaguely defined within all referenced tightening specifications, leading to varying pretension depending on the strength of personnel tightening and the length of the wrench used; a condition that is discussed in further detail in Chapter 6. Second, there are inconsistencies and discrepancies relating to minimum installation pretension and recommended nut rotations for anchor rod tightening; these issues are covered in detail in Chapter 3. An improperly tightened connection as a result of these discrepancies and inconsistencies can lead to variable service level stresses on the anchor rods and can contribute to the nuts' potential loosening due to wind-induced vibrations.

There is also past experimental and analytical evidence showing that transverse and axial vibrations can lead to either the partial or complete loosening of nuts (Bickford 2008; Goodier and Sweeney 1945; Jiang et al. 2003, 2004; Junker 1969; Yamamoto and Kasei 1984). These studies have shown that loss in pretension is a function of the number of vibratory cycles. The effect of wind-induced vibrations on anchor nut loosening is presented in detail in Chapter 5.

Galvanization and overtapping of threads also pose another concern. Anchor rods and nuts are galvanized to increase their service life by preventing corrosion. Ovetapping is the process of the making the nut threads slightly larger to accommodate the increase in the dimensional parameters of the anchor rods resulting from galvanization. ASTM F1554 and A563 standards specify allowable zinc build-up and overtapping allowances on the external and internal threads of galvanized fasteners (ASTM 2015a; b). The anchor nuts are also overtapped after galvanization to minimize the likelihood of rejection due to the inability to run the nut up the threads by hand. Improper galvanization, poor quality control, and excessive overtapping can lead to larger gaps between the mating surfaces of the rod and the nut. A loose tolerance fit can potentially lead to loosening of the nuts upon vibration and even reduced pretension following the specified tightening procedure. A thread tolerance study that compared the thread parameters of anchor rods and anchor nuts with the allowable ASTM tolerances is presented in Chapter 6.

Several documented tightening and fatigue studies have been performed on anchor rods and nuts in double nut moment connections in ancillary highway structures. However, these studies either have some discrepancies or do not cover the entire spectrum of diameter/grade of anchor rods currently used. Some of these studies and discrepancies are addressed in Chapter 2 in detail. There has been minimal previous research performed in the field that examines the loosening of anchor nuts due to wind-induced vibrations. Therefore, the phenomenon and causes of anchor nut loosening along with proper installation of anchor rods in ancillary structures is not well understood and requires further research. The different potential causes of anchor nut loosening, like improper tightening, wind-induced vibrations, and thread tolerances, are investigated in this research study and discussed in detail in this report.

1.2 Dissertation Organization

This dissertation is organized as per the manuscript format—three chapters have been replaced by manuscripts that have been submitted to peer-reviewed journals and international conferences and are under review at the time of final dissertation submission. All of the manuscripts in this dissertation appear in their most refined format, either as the submitted version, or based on improvements made during the peer-review process.

Following Chapter 1 (Introduction), Chapter 2 provides a brief literature review of the problem pertaining to loose anchor nuts on ancillary structures. It address the relevant literature on topics such as types of anchor rod connections, types of wind loadings, theory of self-loosening, and problems associated with ancillary structures. The literature and research topics that address historical loosening events, current anchor rod tightening guidelines, past field monitoring studies, past vibration and fatigue testing, are discussed in detail at the beginning of each subsequent chapter. Chapter 3 presents the manuscript "Tightening Procedures for Proper Installation of Anchor Rods in Ancillary Structures," submitted to the American Society of Civil Engineering (ASCE) Journal of Structural Engineering on 09/30/2019. This manuscript reviews the current tightening procedures for double-nut moment connections in ancillary structures and recommends new changes on the basis of the discrepancies found as a result of a tightening study. Chapter 3 also includes an additional section on appropriate tightening procedures for single-nut connections in ancillary structures.

Chapter 4 consists of detailed description of a four-month field monitoring study performed on a traffic signal and a luminaire in Carrollton, Virginia. The anchor rod stress data from the field monitoring was further used for full-scale vibration testing as discussed in the next chapter. Chapter 5 presents the manuscript "Investigation of Anchor Nut Loosening on Highway Ancillary

Structures," submitted to the ASCE Journal of Structural Engineering on 03/05/2020. This manuscript discusses the effects of wind-induced vibrations on loosening of anchor nuts in ancillary structures. The relationship between initial anchor rod pretension, number of vibration cycles, vibration stress range, and nut loosening was evaluated as a result of large-scale testing. Further, small-scale testing on double-nut moment connections in ancillary structures was conducted to verify the large-scale testing results.

Chapter 6 presents the manuscript "Effect of Thread Fabrication Tolerance and Snug-tight on the Loosening of Anchor Nuts in Highway Ancillary Structures," submitted to the ASCE International Conference on Transportation and Development 2020 on 12/16/2020. This manuscript presents results from a thread tolerance study that compared the thread parameters of different diameters of anchor rods with the specified tolerances in ASTM standards. It also evaluates the effect of variable wrench length and personnel strength on the loosening of anchor nuts. Chapter 7 provides the conclusions, recommendations, and future work from the research project.

1.3 Attribution

The research work reported in this dissertation has been supported and funded by the Virginia Transportation Research Council (VTRC). The manuscripts "Tightening Procedures for Proper Installation of Anchor Rods in Ancillary Structures", "Investigation of Anchor Nut Loosening on Highway Ancillary Structures", and "Effect of Thread Fabrication Tolerance and Snug-tight on the Loosening of Anchor Nuts in Highway Ancillary Structures" are co-authored by the project Principal Investigator, Dr. Matthew Hebdon.

1.4 Research Purpose and Scope

The overall purpose of this research project is to determine the causes behind loosening of anchor nuts on ancillary structures. Potential causes including wind-induced vibrations, proper installation of anchor nuts, and thread fabrication tolerance were experimentally investigated. The study also recommends methods or measures for prevention of the observed anchor nut loosening.

1.5 Research Objectives

The research objectives of this study are to

1. Experimentally verify the existing AASHTO and FHWA tightening procedures for double nut moment connections on steel and aluminum ancillary highway structures. New changes in the specifications are recommended where discrepancies were found.
2. Develop new tightening procedures for anchor rods and nuts in a single nut connection on Transformer Base (T-base) poles.
3. Experimentally investigate the effect of wind-induced vibrations on self-loosening of anchor nuts in a double nut moment connection on a full-scale traffic signal. The parameters that are investigated include vibration stress range and pretension in the anchor rod.
4. Experimentally investigate the effect of axial vibrations on self-loosening of anchor nut on a smaller scale in a fatigue-rated universal testing machine. The parameters that are investigated include vibration stress range and pretension in the anchor rod.
5. Investigate the effect of galvanization and overtapping on the thread fabrication tolerance of the anchor rods and nuts. Variations in thread height, major diameter, minor diameter, pitch diameter, and flank angle are investigated.

6. Investigate the variation in snug-tight pretension due to different wrench lengths and applied torque in a double-nut moment connection.

1.6 Research Plan

This research project includes the following tasks:

1. Tightening procedures for double nut moment connections on ancillary structures (Chapter 3)
2. Tightening procedures for anchor nuts on transformer base (T-base) poles (Chapter 3)
3. Four-month field monitoring program on two in-service ancillary structures (Chapter 4)
4. Large-scale vibration testing on full-scale traffic signal to evaluate the effect of wind-induced vibrations (Chapter 5)
5. Small-scale vibration testing on a single anchor rod to validate the results from large-scale testing (Chapter 5)
6. Thread fabrication tolerance study to investigate the effect of galvanization and overtapping on threads (Chapter 6)
7. Snug-tight study to investigate the effect of wrench lengths and personnel strength on snug-tight pretension (Chapter 6)

The research work reported in this dissertation was supported and funded by the Virginia Transportation Research Council (VTRC). The laboratory testing in this research project was conducted in the Thomas Murray Structures Laboratory at Virginia Tech, Blacksburg, VA. All the equipment used during the project were property of Virginia Tech. However, external support in the form of bucket truck, electrical work, and crew during the field monitoring task was provided by the Virginia Department of Transportation (VDOT).

CHAPTER 2: Literature Review

This chapter offers a brief literature review of the terminology and theory associated with types of anchor rod connections, types of wind loadings, past problems observed in ancillary structures, self-loosening, transverse/axial vibrations, current tightening procedures, and past vibration testing on ancillary structures. A thorough literature review involving each topic is provided in detail at the beginning of each subsequent chapter.

2.1 Anchor Rod Connections

There are two types of anchor rod connections used in ancillary structures:

1) Threaded-Shear-and-Uplift Connection–Also called the single nut connection, this type of connection consist of a single nut on the anchor rod that is used to fasten the base plate to a concrete foundation (Figure 1). There is generally a grout pad between the base plate and concrete foundation. The anchor nuts on the top are pretensioned, but these connections develop only some resistance to bending moment and are not typically considered a moment connection (Garlich and Thorkildsen 2005). These connections are not good in retaining pretension under cyclic loads due to the wearing of the grout pad and concrete foundation. Single nut connections are currently only required to be tightened using an ordinary wrench with full effort of the worker. In case the connection is designed for seismic or fatigue loads, it is necessary to fully pretension the anchor rods (Dexter and Ricker 2002). Since single-nut connections are not considered a moment connection, these are mostly used in small structures such as luminaires and small diameter traffic signal poles due to the relatively smaller induced bending moment at the base.

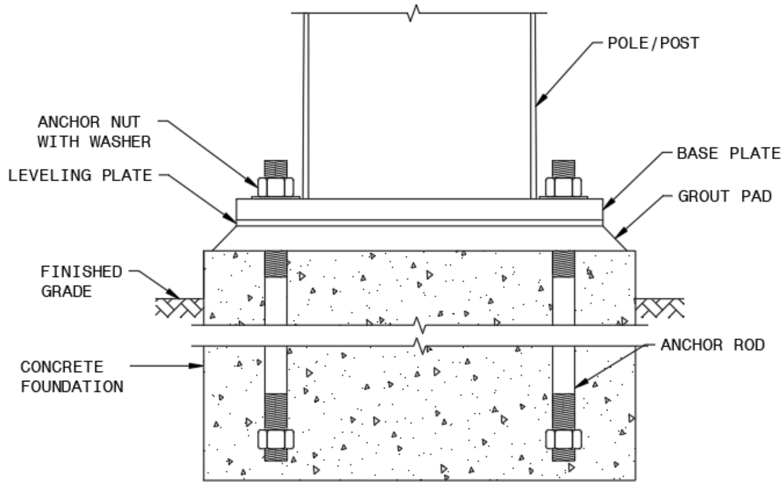

Figure 1. Threaded-Shear-and-Uplift Connection

2) Double-Nut Moment Connection –This type of connection consists of a two nuts on either side of a base plate with a stand-off distance from a concrete foundation (Figure 2). The anchor rods are fully pretensioned using two nuts (a top nut and a leveling nut) by following a turn-of-the-nut tightening procedure. The turn-of-the nut procedure involves tightening the nuts in a star tightening pattern in at least two increments according to the specified nut rotations. This type of connection detail is capable of resisting moments and, hence, can be used on any ancillary structure. The pretension in the anchor rod does not add to the strength of the connection but provides slightly better fatigue resistance and ensures proper distribution of load among the anchor rods (Kaczinski et al. 1998).

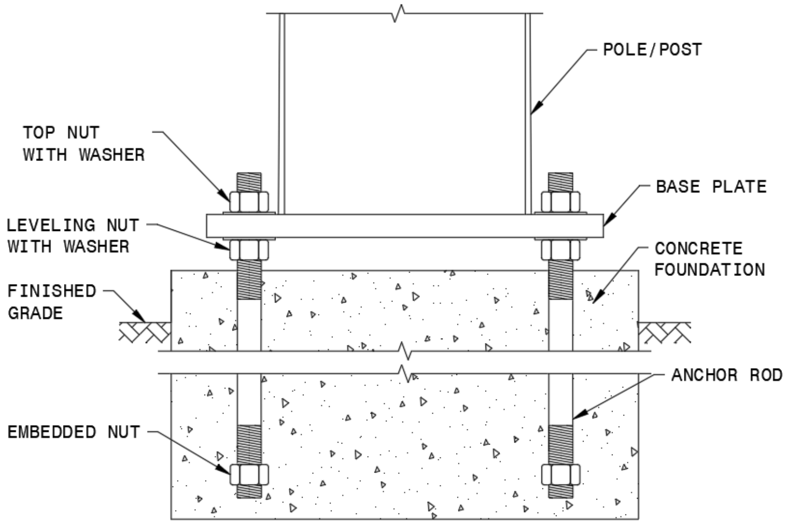

Figure 2. Double-Nut Moment Connection

Structural steel connections tightened using turn-of-the-nut procedures, which face problems of self-loosening of nuts, fatigue or exposure to dynamic loads, are recommended to be fully pretensioned with preloads equal to 85%-100% of the yield strength (Bickford 2008). Moreover, there has been prior evidence of pretension loss and nut loosening (initial relaxation) after the first few days of tightening in double-nut moment connections (Dexter and Ricker 2002). Initial short-term relaxation can be due to a combination of many factors, such as creep of metal parts, differential thermal expansion, and embedment relaxation (Bickford 2008) . However, the anchor rods are also required to be tightened to 110% of a verification torque 48 hours after the initial tightening to overcome this initial relaxation (AASHTO 2015; Garlich and Thorkildsen 2005). There are no other measures specified in the tightening guidelines for the prevention of loosening of anchor nuts or measuring the pretension in the anchor rod in the field after tightening.

2.2 Wind Loading

Four types of wind loading phenomenon act on ancillary structures:

1) Natural Wind Gusts – Natural wind gusts are variable frequency and high-speed winds typically blowing horizontally causing variable frequency vibrations in different types of ancillary structures (cantilevered sign, cantilevered signal, luminaires, and high-mast light towers). In cantilevered structures, these gusts cause motion of a cantilevered mast arm of the ancillary structures primarily in the horizontal direction but can be accompanied by some vertical motion as well (Garlich and Thorkildsen 2005). Locations with a mean annual wind velocity of greater than 10 mph are susceptible to fatigue cracking and vibrations in ancillary structures due to natural gusts with many reported cases over the past few decades. Fatigue cracking due to natural gusts has primarily occurred in mast-arm-to-pole connections of luminaires and cantilever signal/sign structures in the past reported cases. However, there have been some incidents of cracking of the welds at the base plate as well.
2) Truck-induced Wind Gusts – Truck-induced wind gusts primarily cause vertical motion of cantilevered mast arms of ancillary structures when trucks pass underneath the mast arm. Variable message sign structures are most vulnerable because of their large frontal exposure area (Kaczinski et al. 1998). These types of gusts cause negligible movement as compared to the natural gusts and, hence, are ignored in the design specifications (Garlich and Thorkildsen 2005).
3) Vortex-shedding – Vortex shedding is defined as the detachment of vortices periodically from either side of a symmetric member. This pattern involving the shedding of vortices behind the structure is also known von Karman Vortex Street (see Figure 3). Vortex shedding can result in resonant motion of the support structure in a direction perpendicular to the wind direction. Only luminaires have experienced problems in the past due to vortex

shedding. However, other cantilevered structures may be susceptible (Garlich and Thorkildsen 2005). Aluminum luminaires are typically susceptible to vortex shedding at locations with uniform steady state wind velocities in the range of 10 to 35 mph (Kaczinski et al. 1998). Fatigue cracking in aluminum luminaires due to vortex-shedding typically occurs at the weld connecting the base plate to the pole, hand holes, transformer bases, and stiffeners (Garlich and Thorkildsen 2005).

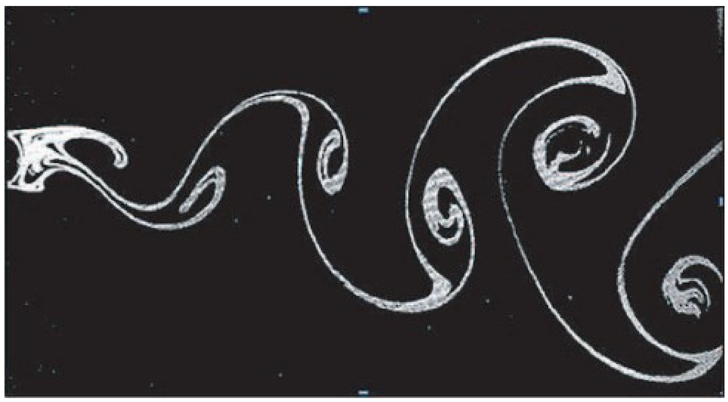

Figure 3. von Karman Vortex Street (Anderson 2007). Reproduced with permission from McGraw Hill.

4) Galloping – This wind phenomenon causes large vibrations in a direction perpendicular to the wind direction similar to the vortex shedding (Johns and Dexter 1998). However, unlike vortex shedding, galloping primarily occurs in asymmetrical members (such as in cantilevered structures) as compared to circular members (such as in luminaires). Galloping causes vertical movement of the mast arm and also requires uniform steady winds at a lower frequency of around 1 Hz (Garlich and Thorkildsen 2005). Most of the fatigue cracking cases due to galloping in the past have occurred at the mast-arm-to-pole connection and at the base plate weld.

2.3 Problems Associated with Ancillary Structures

Collins and Garlich list some of the common problems associated with ancillary structures observed during inspection across the different states in the United States (1997):

- Cracked anchor rods in the standoff distance and inside the foundation
- Fatigue cracks around the hand hole, at the base plate weld, mast-arm-to-pole connection weld, welds around stiffener, and truss connection weld (tube-to-tube)
- Loose or missing anchor rods
- Excessive vibrations of support structures due to vortex shedding, galloping, and natural gusts
- Traffic-induced vibrations of bridge luminaries
- Corroded anchor rods and nuts
- Clogged drain holes and debris accumulation

2.4 Current Tightening Procedures

Turn-of-the-nut tightening procedures are recommended for tightening of anchor rods onto foundations in ancillary structures (AASHTO 2015). The tightening procedures in the AASHTO specifications have been adapted and derived from multiple references, including Till and Lefke (1994), James et al. (1996), Johns and Dexter (1998), National Cooperative Highway Research Program (NCHRP) report 469 (Dexter and Ricker 2002), and FHWA guidelines (Garlich and Thorkildsen 2005). The anchor nuts are required to be tightened incrementally up to a specific rotation past the snug tight condition, and are dependent on the diameter and grade of the anchor rod (see Table 1). The specified nut rotations given in Table 1 ensure that the anchor rod achieves minimum installation pretension (P), which is below the yield strength of the anchor rod grade.

The anchor rod tightening is also recommended to be verified using a verification torque 48 hours after installation to overcome any initial relaxation. The equation for the verification torque was derived by Till and Lefke (1994) and is further adopted in the different tightening specifications (Equation 1).

Table 1. Recommended top nut rotations for turn-of-the-nut tightening (AASHTO 2015)

ASTM F1554 Anchor Rod Diameter (inch) (UNC Threads)	Top Nut Rotation (˚) beyond Snug-tight	
	Grade 36	**Grade 55, 105**
≤ 1½	60	120
> 1½	30	60

$$T = 0.12dP$$

Equation 1. Torque verification equation (Till and Lefke 1994)

Where

T = applied verification torque

d = nominal diameter of the rod

P = minimum installation pretension (50% of the specified minimum tensile strength of F1554 grade 36 rods, and 60% for the F1554 grade 55 and grade 105 threaded rods) (Dexter and Ricker 2002; Garlich and Thorkildsen 2005). It should be noted that the AASHTO specification defines P as a percentage of minimum yield strength instead of tensile strength (AASHTO 2015).

There are a few discrepancies in the existing literature and tightening guidelines or specifications that could lead to under-tightening or over-tightening of anchor rods. For example, grade 55 and 105 anchor rods have different yield strengths but are still grouped under the same category for recommended nut rotations (see Table 1). The grade 55 and 105 anchor rods achieve different levels of pretension when tightened by the same amount of nut rotation. Also, past literature provides evidence suggesting over-tightening or yielding of grade 55 anchor rods as a result of following current required nut rotations for double-nut moment connections (Hoisington et al. 2014; James et al. 1996). There is also inconsistency regarding the minimum installation pretension for the three grades of anchor rods. It is typically recommended to tighten structural connections using a P/Fy ratio of 85-100% if the anchor rods are exposed to dynamic or vibration loads (Bickford 2008). However, FHWA guidelines recommend a P/Fy of 71% for grade 105 anchor rods as opposed to the more acceptable levels of 81% for grade 36 and 55 anchor rods (Garlich and Thorkildsen 2005). On the other hand, the AASHTO specifications require a minimum installation pretension to be a lower value of 50% of F_y for grade 36 anchor rods and 60% of F_y for other grades (AASHTO 2015).

2.5 Snug-tight Condition

The force required to achieve a snug-tight condition, a term important to this study, depends on many factors such as the length of the wrench used, the torque applied, thread lubrication, friction between the threads, and friction between the nut and the plate. The snug-tight condition is a precursor to the final pretension achieved using the turn-of-the-nut procedure in double-nut moment connections. The snug-tight condition is defined differently in various federal and state highway specifications. AASHTO and VDOT specifications define snug-tight as the maximum nut rotation resulting from the full effort of one person using a 12-inch long wrench or equivalent (AASHTO 2015; VDOT 2016a). Other specifications and documents define snug-tight as 20% to 30% of the final pretension or torque verification (Dexter and Ricker 2002; Garlich and Thorkildsen 2005). The specification for structural joints using high-strength bolts defines snug-tight condition as the tightness attained with few impacts of an impact wrench or the full effort of an ironworker using an ordinary spud wrench to bring the plies into firm contact (RCSC 2014).

Based on the literature, a snug-tight condition is vaguely defined and lacks a universally accepted definition.

A recent study by Iowa State University researchers in collaboration with the Minnesota Department of Transportation (MDOT) concluded that controlling snug-tight pretension is critical for the turn-of-the-nut tightening method (Chen et al. 2018). The authors found that 10% of the yield stress of the rod is a more accurate approximation for snug-tight condition than the 20-30% of final pretension definition given in the NCHRP 469 report and FHWA specifications (Dexter and Ricker 2002; Garlich and Thorkildsen 2005). It was also observed that the amount of force applied during snug-tightening is important; variation in this force can either lead to yielding of smaller anchor rods (< 1.5-inch diameter) or under-tightening of larger anchor rods (> 1.5-inch diameter) (Chen et al. 2018). This report suggested using several specific lengths of wrenches for snug-tightening a particular diameter and grade of anchor rod. The range of recommended wrench sizes varied from 1 inch to 100 inch.

2.6 Theory of Self-Loosening

It is believed that wind-induced vibrations in ancillary structures due to the different wind loading phenomenon like natural gusts, vortex-shedding, and galloping contribute to loosening of anchor nuts. Vibrations in the past have led to partial or complete loosening of nuts in structural and mechanical connections (Bickford 2008; Goodier and Sweeney 1945; Jiang et al. 2003, 2004; Junker 1969; Yamamoto and Kasei 1984). Vibrational loosening of nuts is based on the theory of self-loosening, explained in detail in this section.

When a bolt or a rod is pretensioned, it stores energy in the form of tension, torsion, and bending due to deformation. However, this energy held by the frictional constraints can be released by overcoming the frictional forces between the mating threads and between the contact faces of the nut and joint (Bickford 2008). The vibrations in a bolted connection can lead to loss of the frictional forces and in turn, cause the loosening of the nuts. This behavior can be visualized by assuming the threads of the bolt-nut joint as an inclined plane with a block resting on it (Figure 4). The block tends to overcome the friction and slide down under external vibrations. If W is the weight of the block, and θ is the inclination of the block relative to a horizontal plane, W x Sinθ is the gravitational force pulling the block against the frictional force μ x W x Cosθ. If the block is vibrated in any direction, the friction force will be overcome, and the block will slide.

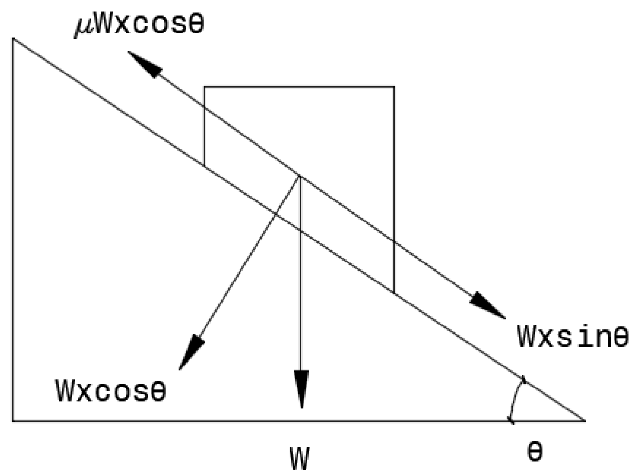

Figure 4. Block and Inclined Plane Analogy for Bolt-Nut Joint

This same principle applies to the nut and bolt connection. The pretension in the bolt is the gravitational force, and frictional force is the friction between the threads and other contact surfaces. It appears that a vibration of the block in any direction should overcome the frictional forces in a connection and cause loosening. However, the loosening of nuts is dependent on the direction of vibration and the initial pretension in the bolt or rod. Previous research shows that transverse vibrations (perpendicular) to the axis of the bolt can cause complete loosening of the nuts (Junker 1969).

2.7 Transverse Vibrations

After Junker, Yamamoto and Kasei, in 1984, also explained the mechanism of self-loosening of bolted connections under transverse vibrations based on torsional bolt deformation. Using experimental and analytical data, they showed that torsional bolt deformation during transverse vibrations could result in an accumulation and release of potential energy, thereby causing self-loosening. According to Jiang et al., the self-loosening mechanism, in general, involves two stages (as seen in Figure 5) (Jiang et al. 2003). The first stage consists of a gradual relaxation of preload accompanied by negligible nut loosening due to the local material deformation or plasticity at the roots. The second stage starts when the preload reaches a threshold value, resulting in a rapid decrease in preload and the nut backing off.

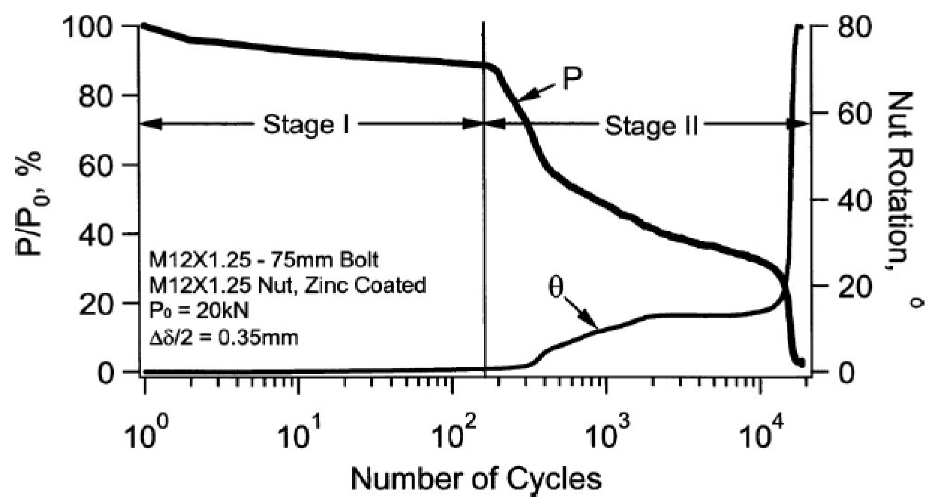

Figure 5. Self-Loosening Curve (Jiang et al. 2003). Reproduced with permission from the American Society of Mechanical Engineers (ASME)

In 2004, Jiang et al. conducted transverse vibration tests on over 100 bolted connections with M12x1.75 bolts and nuts and developed self-loosening curves similar to fatigue S-N curves with a threshold value. They found that higher pretension in the bolt resulted in greater resistance to loosening by transverse vibrations. Further, German researchers investigated the effect of clamp length on self-loosening of bolts (Friede and Lange 2009). The investigation involved pretensioning of M20-10.9 bolts to 36 kip followed by the vibration of the joint in the transverse direction at an amplitude of +/- 0.078 inches and a frequency range of 0.2 to 1 Hz. The results showed that a longer clamp length resulted in better resistance to the self-loosening mechanism.

2.8 Axial Vibrations

There has been no documented evidence until now suggesting that axial vibrations (parallel to the axis of the bolt) can result in total loss of preload (Bickford 2008). Early research in the 1940s showed that dynamic axial loading in ¾-10 nuts resulted in partial loosening of the nuts (around 2˚ of nut rotation) in 500 vibratory cycles (Goodier and Sweeney 1945). The bolts were loaded in tension repeatedly from 500 lb to 6000 lb in a tensile testing machine. There was evidence of alternating tightening and loosening during the loading-unloading cycles which was later referred to as frictional ratcheting.

Sauer et al. (1950) evaluated the effect of axial vibrations on loosening of nuts instead of quasi-static loading as done by Goodier and Sweeney. As part of the testing, 5/16 – 18 screws were axially vibrated at varying levels of dynamic load (vibrations) to static load (pretension) ratio (DSR). Their axial vibration research revealed that the rate of nut loosening was significant during the first 500 cycles but fell rapidly beyond that up to 20000 cycles (Sauer et al. 1950). For example, during one of the tests, the dynamic load was fixed at 250 lb and static load was varied from 250 lb to 1000 lb. It was observed that the rate of loosening was a function of the ratio of dynamic to static load (pretension) ratio and the amount of loosening decreased with an increase in bolt pretension. The DSR of 250/250 produced approximately 1.5˚ of nut rotation and DSR of 250/1000 produced less than 0.25˚ of nut rotation after 100 vibration cycles. Sauer et al. also recommended to keep the DSR less than 0.7 to avoid any loosening issues.

Gambrell (1968) performed a series of experiments to analyze the effect of thread type (finer vs coarse) on loosening of nuts due to axial vibrations. During the testing, axial cyclic loads were applied to the 5/16 inch nut-bolt connection by a variable-speed electric motor. The fasteners were loaded to their yield stress of 55 ksi and subjected to variable DSRs. It was concluded from the results that an increase in DSR increases the loosening of both thread types and also that the rate of loosening decreases after the first few thousand cycles of vibration. One of the other research studies stated that the clamping force in a bolted assembly subjected to axial vibrations can increase, decrease, or remain steady depending on the level of applied vibration and pretension in the assembly (Basava and Hess 1998).

2.9 Thread Fabrication Tolerance

Thread type, class, configuration, and fit affect not only the strength of the connection but also the resistance to self-loosening and fatigue (Bickford and Nassar 1998). Structural connections are typically required to have a tight fit between the mating threads to avoid any issues with strength and resistance. Galvanization is performed on the anchor rods and anchor nuts in ancillary structures as a precautionary measure against corrosion, and anchor nuts are overtapped after galvanization to ensure a proper fit between the mating threads. ASTM F1554 and ASTM A563 specify tolerances on the allowable zinc build-up on the anchor rod and overtapping on the anchor nuts, respectively (ASTM 2015a; b). The anchor rod and nut thread parameters including major diameter, minor diameter, pitch diameter, and flank angle are required to be within the allowable tolerances after the galvanization and overtapping process. This ensures that there are no undesirable gaps between the mating threads that could lead to relative motion between the threads and contribute to nut loosening or reduced strength. Past research also showed that loose thread fit and larger thread clearance between the mating threads of a bolt and nut assembly leads to an exponential increase in the rate of nut loosening under the effect of transverse vibrations (Nassar and Housari 2007). Bolted connections subjected to dynamic vibration loading are equipped with fastener locking techniques like jam nuts, lock nuts, lock washers, serrated nuts, serrated washers, and chemical adhesives to prevent any slip or friction loss between the mating threads and joint surfaces (Bickford 2008; Bickford and Nassar 1998).

2.10 Vibration Testing of Ancillary Structures

A majority of the research on ancillary structures has been related to field testing that focused on understanding the dynamic behavior of ancillary structures like HMLTs, sign structures, and luminaires, and also identification of the fatigue limit states associated with each structure type (Connor et al. 2012; Connor and Hodgson 2006; Foutch et al. 2006; Hoisington et al. 2014; McLean et al. 2004; Phares et al. 2007; Zuo and Letchford 2008). Some of the past research also involved large-scale testing related to fatigue and weld crack issues (Alderson 1999; Archer and Gurney 1970; Dechant 1996; Koenigs et al. 2003; Miki et al. 1984; Miki and Masakaju 2001; Ocel et al. 2006; Puckett et al. 2010; Sherman et al. 2016; Stam et al. 2011; Thompson 2012). Very few research projects have investigated the loosening aspect of anchor nuts on ancillary structures specifically (Chen et al. 2018; Hoisington et al. 2014; Nassar and Matin 2006).

One recent study that did so focused on loosening of anchor nuts on ancillary structures and included large-scale testing of a straight pole (Type 5 signpost) from the Minnesota Department of Transportation (MnDOT) (Chen et al. 2018). Twelve grade 55, 2.5 inch diameter anchor rods on the ancillary structure were tightened to 75% yield with a 450 ft-lb torque. Three out of the 12 anchor rods were accidentally yielded during tightening. The signpost was loaded cyclically at a frequency of 1 Hz using a hydraulic actuator at the free end. The target axial stress was set at 6 ksi in the rods, which was determined as a result of field monitoring data. During testing, one of the twelve anchor rods on the ancillary structure were found to have a loose nut after 2000 cycles of a 6 ksi stress range. The nut tightness was checked by striking or sounding of the washers with a hammer, which is the technique currently used in the field by MnDOT maintenance crew. The nut tightness was also checked by loosening of the nut using a torque wrench and the inspected loose nut began to turn at 180 ft-lbs indicating that the nut was only partially loose. After this test, another fatigue test was conducted at a vibration stress range of 1 ksi. However, no loosening was observed after 1.24 million cycles.

CHAPTER 3: Tightening Procedures for Anchor Rods in Ancillary Structures

Chapter 3 consists of 3 sections – 3.1, 3.2, and 3.3. Section 3.1 presents an under-review manuscript "Tightening Procedures for Proper Installation of Anchor Rods in Ancillary Structures" submitted to the Journal of Structural Engineering on 09/30/2019. The manuscript provides a review of the current tightening procedures for double-nut moment connections in ancillary structures and recommends new changes on the basis of the discrepancies found in the current tightening procedures. Section 3.2 presents results from an experimental tightening study on single-nut connection on transformer base (T-base) poles. Section 3.3 provides information regarding the recommended revised tightening procedures for double-nut and single-nut connections in ancillary structures.

3.1 Tightening Procedures for double-nut moment connections in ancillary structures

Japsimran Singh[1], Matthew H. Hebdon[2]

3.1.1 Abstract

In the past two decades, many ancillary structures have collapsed, with several instances traceable to loose anchor nuts. According to a quality assurance inspection conducted by the Virginia Department of Transportation (VDOT) in 2012, approximately 30% of the anchor nuts on the inspected ancillary structures across the state of Virginia were found to be loose. The exact cause of the loose anchor nuts is not known, however, one theory is that specified tightening procedures were not properly followed, or were not adequate. Currently, a turn-of-the-nut method is used for the tightening of anchor nuts on double-nut moment connections at the base of ancillary

[1,2] Department of Civil & Environmental Engineering, 200 Patton Hall, Virginia Tech, Blacksburg, VA 24060

structures. The purpose of this research was to review current tightening procedures for anchor nuts on ancillary structures. In doing so, the relationship between three critical tightening parameters, applied torque, nut rotation, and pretension in the rod, were examined. One hundred galvanized steel anchor rods, of five different diameters and three different grades were tested. The experimental tests serve as a benchmark to validate the current tightening procedures, as well as to recommend changes.

3.1.2 Introduction

Loose anchor nuts on ancillary structures have resulted in failures of several structures in the transportation industry. Ancillary highway structures include overhead sign structures, luminaries, traffic signals, and high-mast light towers. Structural steel joints tightened by turn-of-the-nut procedures, which potentially are susceptible to self-loosening of nuts, fatigue, or exposed to dynamic loads should be fully pretensioned with preloads up to 85-100% of yield strength (Bickford 2008). Previous research suggests that a fully tightened anchor nut and the rod would prevent any loosening under service loads (Dexter and Ricker 2002). However, two potential primary causes of loosening are believed to be 1) over-tightening (resulting in yielding of anchor rods) and 2) under-tightening (Chen et al. 2018).

The transportation industry's current tightening procedures specified in the American Association of State and Highway Transportation Officials (AASHTO) Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (AASHTO 2015) have been adapted from tightening procedures provided in the Federal Highway Association (FHWA) guidelines (Garlich and Thorkildsen 2005). The tightening procedures in the FHWA guidelines and AASHTO specifications have been derived from results of multiple research studies, including Till and Lefke (1994), James et al. (1996), Johns and Dexter (1998), and National Cooperative

Highway Research Program (NCHRP) report 469 (Dexter and Ricker 2002). The tightening procedures specify a turn-of-the-nut tightening method for installation of anchor rods on ancillary structures. This tightening method involves tightening the top anchor nut in angular increments up to a specific rotation based on the diameter and grade of the rod as given in Table 2.

Table 2. Required Top Nut Rotation (AASHTO 2015)

Anchor Rod Diameter* (inch)	Top Nut Rotation (˚) beyond Snug-tight **	
	F1554	
	Grade 36	Grade 55, 105
≤ 1½	60	120
> 1½	30	60

*UNC threads only

**Top nut rotation is relative to anchor rod. Tolerance is plus 20˚

The specified required nut rotation is intended to ensure that the rods develop the minimum installation pretension (P), which is below the specified yield strength of the rod. The minimum pretension prevents any yielding of the rods during the installation. It also allows for retightening after an initial relaxation of pretension in the rods (Till and Lefke 1994). Therefore, current AASHTO specifications (2015) and FHWA guidelines (2005) specify a verification torque of 110% of the required pretension to be applied 48 hours after initial tightening to overcome any initial anchor rod relaxation. Equation 2 derived by Till and Lefke, defines the verification torque, as specified in the installation sequence for double nut moment connections in FHWA guidelines (Garlich and Thorkildsen 2005) and NCHRP 469 (Dexter and Ricker 2002).

$$\mathrm{T} = 0.12 * \mathrm{d} * \mathrm{P}$$

Equation 2. Torque Verification Equation (Till and Lefke 1994)

Where:

T = applied verification torque

d = nominal diameter of the rod

P = minimum installation pretension (50% of the specified minimum tensile strength of F1554 Grade 36 rods, and 60% of the specified minimum tensile strength of the F1554 Grade 55 and Grade 105 anchor rods)

However, AASHTO specifications (AASHTO 2015) define P as a percentage of the yield strength of the rods instead of the tensile strength as specified in FHWA guidelines (Garlich and Thorkildsen 2005) and NCHRP 469 (Dexter and Ricker 2002). Therefore, there is a discrepancy regarding the minimum pretension values in the above documents.

3.1.3 Literature Review

Grouping of grade 55 and 105 anchor rods

Limited research data exist evaluating the correlation between pretension and nut rotation for high strength anchor rods (grade 105) and anchor rods with a diameter less than 1.5 inch. The Michigan Department of Transportation (MDOT) conducted some of the earliest research on the correlation between pretension and nut rotation (Till and Lefke 1994). The researchers evaluated the tightening of large diameter anchor rods (1.5 inch, 2 inch, and 2.5 inch). Two of the three diameter rods (1.5 inch and 2.5 inch) tested were grade 55 rods. The 2 inch anchor rod tested was grade 105 with an average yield strength of 103 ksi from material testing. However, the pretension and nut rotation data suggested that the yield behavior was closer to that of grade 55 rods and not grade 105 rods. Therefore, all the reported nut rotation recommendations in the report are applicable for only grade 55 rods. However, the grade 105 anchor rod results from the research have been further referenced in the AASHTO specifications (AASHTO 2015).

The current AASHTO specifications group grade 55 and grade 105 anchor rods together (see Table 2). However, grade 55 and 105 have different yield strengths and, therefore, achieve different levels of pretension when tightened to the same nut rotation. Therefore, grade 55 and grade 105 should not be grouped under the same nut rotations as currently specified. This discrepancy in the current tightening specifications can either lead to over-tightening of the lower grade 55 rods or under-tightening of the higher grade 105 rods.

Grouping of 1.5 inch Diameter Anchor Rods

Another discrepancy is apparent based on a review of the research (Till and Lefke 1994) and the implementation documents (AASHTO 2015; Dexter and Ricker 2002; Garlich and Thorkildsen 2005). Till and Lefke grouped 1.5 inch anchor rods with larger anchor rods for recommended turn-of-nut procedures (30° for Grade 36, and 60° for Grades 55 and 105). However, in subsequent publications and standards, the 1.5 inch diameter anchor rods are grouped with smaller anchor rods for required turn-of-nut procedures (60° for Grade 36, and 120° for Grades 55 and 105) even though each of these documents (AASHTO 2015; Dexter and Ricker 2002; Garlich and Thorkildsen 2005) reference the research performed by Till and Lefke .This discrepancy can lead to the over-tightening of the 1.5 inch anchor rods as per the present specifications.

Evidence Showing Over-tightening of Grade 55 Anchor Rods

Results from two other research studies show that tightening as per the present specifications leads to over-tightening of larger diameter grade 55 anchor rods (Hoisington et al. 2014; James et al. 1996). Grade 105, 2 inch diameter anchor rods on a cantilevered overhead sign structure (COSS) and Grade 105, 2.25 inch diameter anchor rods on a high mast illumination pole (HMIP) were tested as part of one of the tightening studies at Texas A&M University (James et al. 1996). The anchor nuts on the COSS were rotated 60˚ beyond the snug-tight condition and the average tensile stress induced was found to be 69.3 ksi and 66.7 ksi at two locations within the base plate region. The nuts on the HMIP were also rotated 60˚ beyond the snug-tight condition, and the average tensile stress induced was found to be 62.7 ksi at two locations within the base plate region. The researchers concluded that the required nut rotation of 60˚ for 2 inch and 2.25 inch diameter would yield the grade 55 rods (James et al. 1996). Researchers at the University of Alaska in collaboration with Alaska DOT conducted a similar study where axial force in the rods of a High-mast lighting pole (HMLP) was measured during field tightening (Hoisington et al. 2014). The grade 55 anchor rods were 1.5 inch in diameter. At the specified 60˚ nut rotation, it was found that two out of the twelve rods yielded.

Minimum Installation Pretension

There is also inconsistency among the recommended minimum installation pretension for the three grades of anchor rods in the specification documents (AASHTO 2015) and guidelines (Dexter and Ricker 2002; Garlich and Thorkildsen 2005). According to FHWA guidelines (2005) and NCHRP 469 (2002), the minimum installation pretension value should be 50% of F_u for grade 36 anchor rods and 60% of F_u for other grades. However, the AASHTO specifications require the minimum installation pretension to be a lower value of 50% of F_y for grade 36 anchor rods and 60% of F_y for other grades. Past research has shown that loosening of anchor nuts is unlikely to happen due to the under-tightening of anchor nuts during installation (James et al. 1996) but can happen as a result of the over-tightening or yielding during installation or wind-loading (Hoisington et al. 2014). However, structural connections that experience dynamic loads are recommended to be tightened to 85-100% of the yield strength (Bickford 2008). Therefore, the anchor rods in double-nut moment connections should be tightened close to the minimum specified yield strength to ensure that there is no under-tightening or over-tightening.

The minimum installation pretension values given as a percentage of F_u in FHWA guidelines and NCHRP 469, ensures that the anchor rods are just below the minimum specified yield strength (see Table 3). The minimum installation pretension for ASTM F3125 grade A325 and A490 high-strength bolts is also at least 70% of the minimum specified tensile strength (RCSC 2014). The ratio P/F_y is ~81% and ~91% for A490 and A325 bolts, respectively (ASTM 2018a). Previous research also shows that minimum tightening stress of 60% of the minimum specified tensile strength should be used for lower grade 36 rods to prevent yielding during tightening as opposed to the 70% recommended for high strength bolts (Johns and Dexter 1998). Therefore, the minimum installation pretension values specified in current AASHTO specifications are recommended to be revised to align with the values recommended in FHWA guidelines to prevent any under-tightening or over-tightening.

Table 3. Minimum specified yield and tensile strength (ASTM 2015a) including the minimum installation pretension for different grades of anchor rods (Dexter and Ricker 2002)

Grade	Minimum Yield Strength (F_y) (ksi)	Minimum Tensile Strength (F_u) ksi	Minimum Installation Pretension (P) (ksi)	P/F_y (%)
36	36	58	0.5 F_u	81
55	55	75	0.6 F_u	82
105	105	125	0.6 F_u	71

Other Tightening Studies

Another research study, which focused on the fatigue performance of anchor rods consisted of progressive tightening tests of six diameters of grade 105 anchor rods and short fatigue tests at each increment (Richards 2004). The diameter of rods ranged from 1 inch to 2.25 inch in increments of 0.25 inch. One rod of each diameter was tested and tightened until 60˚ beyond snug-tight. It was found that none of the grade 105 anchor rods yielded at 60˚ nut rotation beyond snug-tight condition. The specimen matrix for the tightening was extensive but did not represent a comprehensive set of tightening data which accounts for variations due to parameters like different grades, lubrication, and grip length.

The Minnesota Department of Transportation (MnDOT) in collaboration with Iowa State University researchers recently published a report evaluating the retightening procedures for large diameter anchor rods on highway support structures (Chen et al. 2018). The research involved testing of grades 36, 55, and 105 anchor rods. The diameter of rods ranged from 1 inch to 2.25 inch in increments of 0.25 inch. The report stresses the importance of achieving appropriate and consistent snug-tight pretension values. The study recommended using specified wrench lengths and maximum snug-tight torque values to achieve snug-tight rod stress equal to 10% of the yield of the rod. The researchers concluded that following the present AASHTO specifications resulted in possible over-tightening of smaller anchor rods (diameter less than 1.5 inch) and under-tightening of larger anchor rods (diameter greater than 1.5 inch). The researchers also found that the grip length was an important factor affecting the relationship between nut rotation and pretension in the anchor rods. It can be concluded from the results in the study that there was an exponential increase in rod deformation (decrease in rod stiffness) when the ratio of the diameter of the rod and grip length was less than 0.6. The rod deformation did not change more than 5% for larger diameter to grip length ratios (0.6-1.2).

3.1.4 Experimental Testing Procedure

As a result of inconsistencies between industry specifications and numerous research studies, anchor rod tightening tests were completed to verify and validate the current tightening specifications. This testing also served as a method to assess the adequacy of the minimum required pretension values in the current specifications. The testing matrix included one hundred galvanized steel anchor rods of diameters ranging from 0.75 inch to 2 inch, and different F1554 material grades (36, 55, and 105) (ASTM 2015a). Two different types of base plate material were used for testing with different rod diameters to align with current industry standards: A36 steel (ASTM 2014a) and 6061-T6 aluminum (ASTM 2014b). Applied torque, nut rotation, and rod pretension were recorded and statistically analyzed to evaluate the correlation between minimum nut rotations and minimum pretension in the rods.

Specimen Matrix

Six base plates - 24 inch x 12 inch, three each of steel (Grade A36) and aluminum (Grade 6061-T6), were used for tightening 100 galvanized steel anchor rods in a double-nut moment connection. Three different grades of rods with the same diameter were tested on each base plate. Most aluminum poles used in ancillary structures across the country have A356-T6 (ASTM 2018b) cast aluminum bases with a single-nut connection as opposed to the popular double-nut moment connection for the cantilevered structures (see Figure 6). Minimum specified yield strength of 6061-T6 grade is 35 ksi as compared to 26 ksi of A356-T6 grade (ASTM 2014b, 2018b). However, since A356-T6 is not available in plate form, 6061-T6 aluminum base plates were used in this testing. Single-nut connection tightening procedures were not tested as part of the research. However, the anchor nuts on single-nut connection joints are recommended by the NCHRP 469 report to be tightened to the same amount of nut rotation as double-nut moment connections if the joint is designed for seismic or fatigue loads (Dexter and Ricker 2002). On the other hand, the AASHTO specification requires tightening of a single-nut connection to only half of the nut rotation for double-nut moment connections (AASHTO 2015).

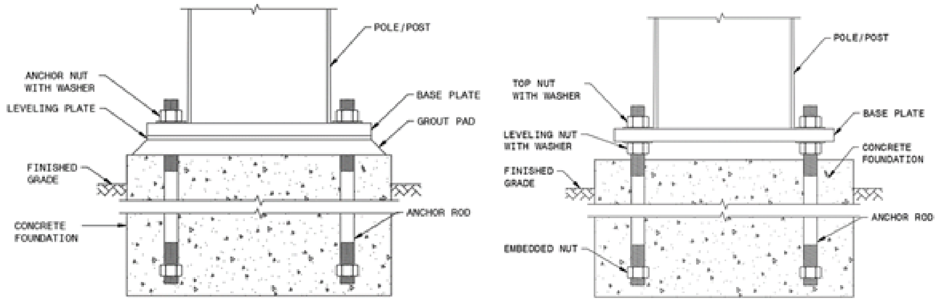

Figure 6. Single-nut connection (left) and Double-nut moment connection (right)

Different base plate thicknesses were used in the testing matrix, and are shown in Table 4. Base plate thicknesses were kept equal to the rod diameter being tested to simulate common industry practice and to avoid any prying effect (Kaczinski et al. 1998). The anchor rod diameters were chosen based upon a survey of common diameters used in ancillary structures in the state of Virginia. Table 4 shows the test matrix, including the different diameter rods tested. Three different grades (Grade 36, 55, and 105) of galvanized steel anchor rods meeting ASTM F1554 (ASTM 2015a) were tested. Each rod had UNC threads. ASTM A563 (ASTM 2015b) and ASTM A194 (ASTM 2016) nuts were used during the testing such that the proof load of the used nut was equal to or higher than the anchor rod's specified minimum tensile strength as per the required nut guidelines in ASTM F1554 (ASTM 2015a). A194 grade 2H nuts are acceptable equivalents of A563 DH nuts and were used in place of A563 DH nuts (ASTM 2015b). Based on the guidelines in ASTM F1554, three galvanized nut grades (A, DH, or 2H) and two galvanized nut styles (hex or heavy hex) were used. Standard F436 (ASTM 2018c) round washers were used throughout the testing.

Table 4. Specimen Matrix for tightening procedures of anchor rods

Anchor Rod			Base Plate (24 inch x 12 inch)	
Diameter (inch)	Grade	Quantity	Grade	Thickness (inch)
1	36	8	A 36 Steel	1
1½		6		1½
2		5		2
1	55	6		1
1½		5		1½
2		5		2
1	105	6		1
1½		4		1½
2		4		2
¾	36	6	6061-T6 Aluminum	¾
1		6		1
1¼		5		1¼
¾	55	5		¾
1		6		1
1¼		5		1¼
¾	105	7		¾
1		6		1
1¼		5		1¼
	Total	100		

Test-setup

Each base plate was connected to the top flanges of two I-shaped beam stubs (W27x217) using 0.875 inch diameter bolts. A 6 inch x 6 inch x 0.75 inch steel reaction angle was attached to each base plate, near the anchor rod hole, as a reaction point for the torque multiplier used in the study. The torque was applied using three calibrated manual torque wrenches with the following capacities: 300 ft-lb, 600 ft-lb and 1500 ft-lb. The output torque was increased as needed by using two torque multipliers with output capacity of 2000 ft-lb and 8000 ft-lb and multiplication ratios of 3.6:1 and 4.6:1, respectively. The nut rotation angle was measured visually using a circular gauge with 360˚ markings around the anchor rod hole. The complete test setup for a 2 inch thick base plate is shown in Figure 7.

Figure 7. Test-setup for a 2 inch thick base plate

Instrumentation

Eight bolt strain gages were installed radially around the anchor rod hole in each base plate. The instrumented strain gages recorded compressive strains in the plate corresponding to the tensile force in the rod during tightening of the nut. Each of the strain gages was placed into 0.078 inch diameter holes drilled near the rod hole, as shown in Figure 8. The holes were drilled to a depth to allow the strain gages to be installed at mid-thickness of the base plate for measurement of the maximum strains in the plate. The holes were located in the plate such that the strain gages were in the centroid of the washer contact area. BTM-6C bolt strain gages from Tokyo Sokki Kenkyujo Co., Ltd. (TML) were used in the instrumentation. The bolt strain gages were installed using the manufacturer's recommended installation procedure.

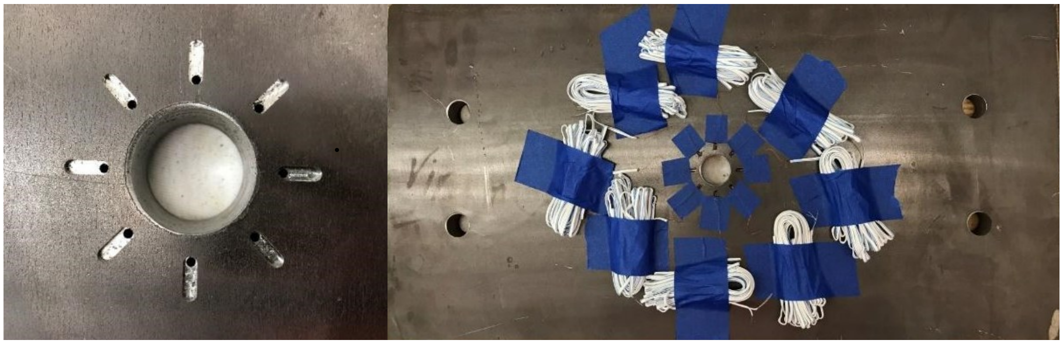

Figure 8. Strain gage holes (left) and 1-inch plate with eight bolt strain gages (right)

A data logger was used throughout the testing for measuring the strains in the plate. The instrumented base plates were calibrated before tightening of the rods to verify that plates were instrumented and working correctly. The compressive strains in the plate around the hole allowed for the calculation of the applied force in the rods. The calibration and verification were performed on a 300 kips capacity Universal Testing Machine (UTM). The UTM was used to obtain a load versus strain calibration curve.

Simulation of the load distribution on the plate during tightening was achieved using washers on the top and the bottom while the plate was loaded in compression. The plate was loaded incrementally, and the corresponding strain values from the eight strain gages were recorded. The strain values recorded from each strain gage were used for calculating an average compressive strain below the washer area. A calibration curve between the average strain and the load was obtained for each plate and each calibration curve was found to be linear with a coefficient of determination (r-squared) greater than or equal to 0.99. Moreover, individual strain gages also showed a linear relationship with the load. The calibration curve was further used while testing to determine the pretension load corresponding to the average compressive strain in the plate recorded by the strain gages on tightening of the top nut.

Six base plates were also modeled in Abaqus 6.14 using 8-noded linear brick elements with reduced integration and hourglass control (C3D8R). Global seed size was chosen as 0.25 inch

However, 40 local nodes were created at the anchor rod hole for mesh refinement (see Figure 9). Base plates were loaded in compression around the washer area and the stress results at the mid-thickness of the plate were evaluated. These compressive stress results for each plate were compared to the calibration stress values calculated using the average of eight bolt strain gages. The FE model results were scattered with the percentage difference between the FE results and the test results varying from a minimum of 6% in the 1.25 inch thick aluminum plate to a maximum of 18% in the 2 inch thick steel base plate. The average percentage difference for the six base plates was found to be approximately 10%.

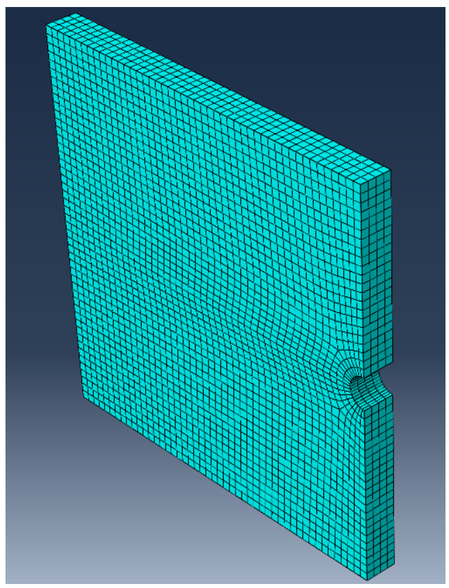

Figure 9. Mesh at the anchor rod hole for the half symmetric model of 1 inch plate

Test Procedure

The tightening procedure specified in the FHWA guidelines (Garlich and Thorkildsen 2005) and AASHTO specifications (AASHTO 2015) was adhered to for the tightening of all anchor rod specimens as follows:

a) The threads of the rod and the leveling nuts were lubricated with a suitable petroleum wax lubricant (Toilet-ring wax: Master Plumber).The flat surfaces of the nuts and washers were also lubricated for the ease of tightening.

b) Both nuts were turned onto the rod, and it was confirmed that they could be rotated with ease.

c) A circular gauge with 360-degree markings was attached around the rod hole for measuring nut rotation.

d) The anchor rod was placed in the hole. The washers and nuts were turned onto the rod by hand until they made contact with the face of the base plate.

e) A wrench was fixed to the bottom of the base plate to prevent the bottom nut from rotating during the tightening procedure.

f) The top nut was rotated to a snug-tight condition using an 18 inch or 24 inch long adjustable wrench, depending on the nut size. The pretension in the rod at the snug-tight condition was measured and recorded using the strain gages in the base plate. It should be noted that the snug-tight condition was assumed to be achieved when the top nut, bottom nut, and the washers were in full contact with the base plate using the maximum work effort of the installer with a wrench (Garlich and Koonce 2010). The snug-tight condition stress was within 1-10 ksi depending on the diameter of the rod, the grade of the rod, friction between the nut and washer, and applied lubrication.

g) A mark was made on the top nut, rod, and top washer indicating the 0˚ mark.

h) The top nut was rotated beyond the snug-tight condition using a manual torque wrench and torque multiplier. Different combinations of the wrench and multiplier were used depending on the torque requirement for the size of the rod.

i) The torque was applied in increments, and the corresponding relative top nut rotation and pretension in the rod were recorded.

j) The test was stopped after there was a large increase in the nut rotation during tightening indicative of the yield of the tested anchor rods.

3.1.5 Experimental Test Results

Maximum values of actual material yield and tensile strength of the anchor rod specimens, as reported in the mill certifications provided by the supplier, are listed in Table 5.

Table 5. Maximum reported yield and tensile strength (Mill Certifications)

Diameter of the rod (inch)	Strength of rod (ksi)*					
	Grade 36		Grade 55		Grade 105	
	Yield	Tensile	Yield	Tensile	Yield	Tensile
¾	44.9	66.5	61.8	81.8	132	142.8
1	56	74.5	62.5	82.3	124	139
1¼	43.7	65	63.7	85	127	141
1½	45.3	69	58.8	80.2	130	145
2	42.2	65.5	65	88.9	125	140

*Based on bar stock testing

Grade 55 – 1 inch diameter anchor rods (Steel Base Plate)

To demonstrate the testing methods, the results from testing six grade 55 – 1 inch diameter anchor rods are discussed in detail. The other grades and diameters of anchor rods were tested similarly. The measured compressive load from the bolt strain gages in the base plate during tightening was divided by the tensile stress area of the tested anchor rod given in ASTM F1554 (ASTM 2015a) to calculate the axial stress in the rod. The six rods were tightened beyond a sudden large change in the slope of 'Stress versus. Nut Rotation' curve, indicating the yielding of the rods.

The maximum reported yield and tensile strength for the rods were 62.5 ksi and 82.3 ksi, respectively, as shown in Table 5. The 'Stress versus. Nut Rotation' curve for grade 55 rods showed a constant initial slope until approximately 70˚ of the nut rotation for all six of the rods, at which point the behavior became bilinear, indicating the location of the yield point (see Figure 10). The mean axial stress in all of the rods at 70˚ rotation was slightly above the maximum reported yield strength of 62.5 ksi. Also, the mean nut rotation corresponding to the minimum specified yield strength of 55 ksi in the tested rods was 60˚. However, the FHWA guidelines (2005) and NCHRP report (2002) recommend the minimum installation pretension of 45 ksi equal to 0.6 times the minimum specified tensile strength of 75 ksi for grade 55 rods. AASHTO specifications (2015) on the other hand, require the minimum installation pretension of 33 ksi equal to 0.6 times the minimum specified yield strength of 55 ksi. As per the results, the mean nut rotation corresponding to the axial stress of 45 ksi was found to be 49˚ as opposed to currently specified turn-of-the-nut requirement of 120˚ in the FHWA guidelines (2002) and AASHTO specifications (2015) (see Figure 10)

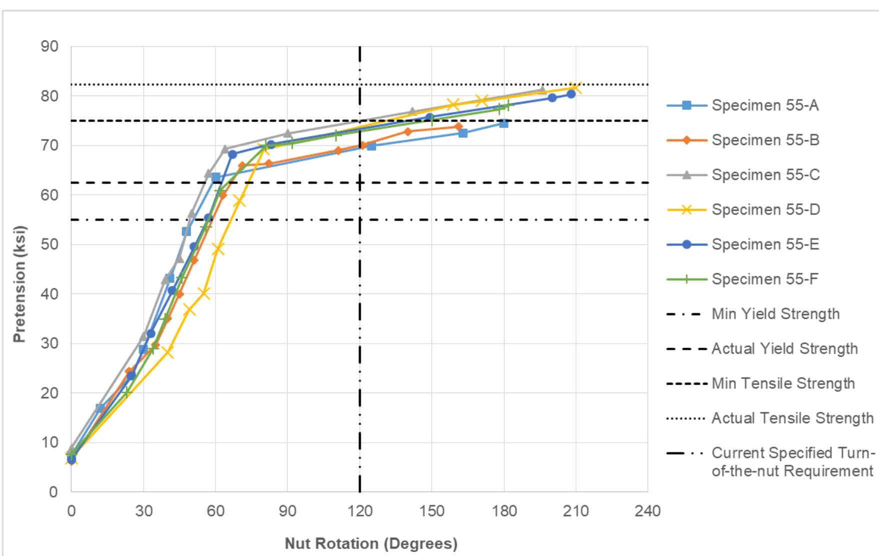

Figure 10. Stress vs. Nut Rotation for grade 55 – 1 inch diameter anchor rods

Torque was also recorded during the tests to determine a relationship between torque and axial stress in the anchor rods. The 'Stress versus. Torque Applied' curves for the six grade 55 - 1 inch diameter rods remained linear until the yielding of the rods (see Figure 11). The behavior became bilinear beyond this point, similar to the 'Stress versus. Nut Rotation' curve. The snug-tight torque was not measured because it was applied using an adjustable wrench, and therefore, these values are not shown in Figure 11. The torque curves shown in Figure 11 had more variation than the nut rotation curves shown in Figure 10 because the torque applied is a function of lubrication and friction between the threads, nuts, and plate. The mean slope of the 'Torque versus Stress' curve for the six rods was found to be 0.11 which is close to the 0.12 value of the K-factor or slope of the verification torque (K = T/Pd) (see Figure 11).

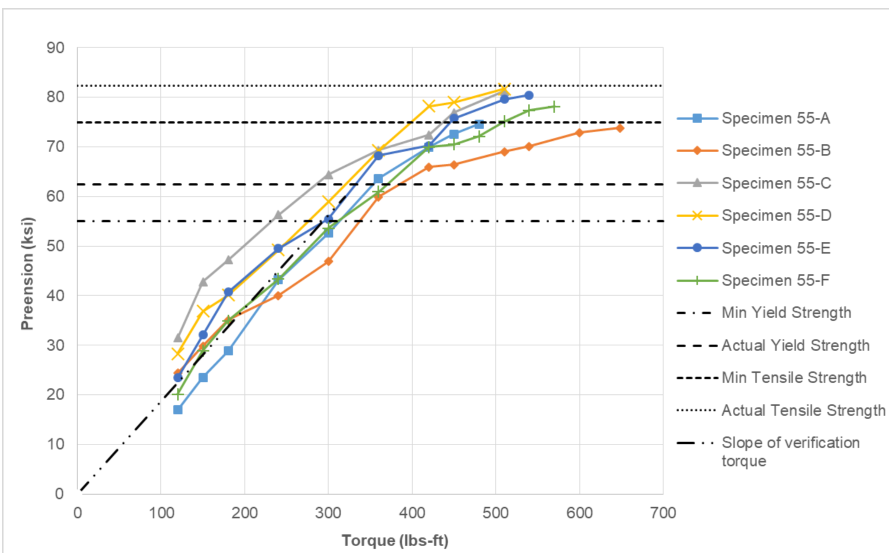

Figure 11. Stress vs. Torque applied for grade 55 –1 inch diameter anchor rods

Combined stress vs. nut rotation curves

'Combined Stress versus. Nut Rotation' curves are shown in; each subplot is comprised of results for a specified anchor rod diameter but three different material grades (36, 55, and 105). Regardless of material properties, each of the rods followed the same initial linear slope until their respective yield strength. Some of the grade 36 rods yielded beyond their maximum reported yield strengths (see Figure 12 (a) and (b)). For example, grade 36, 1 inch diameter anchor rods with a steel base plate yielded near their actual tensile strength (see Figure 12 (a)). The maximum reported yield strengths in this research study are based on the results from bar stock testing and can be higher than the actual yield strength of the anchor rods observed during the tightening study due to the difference in testing methods.

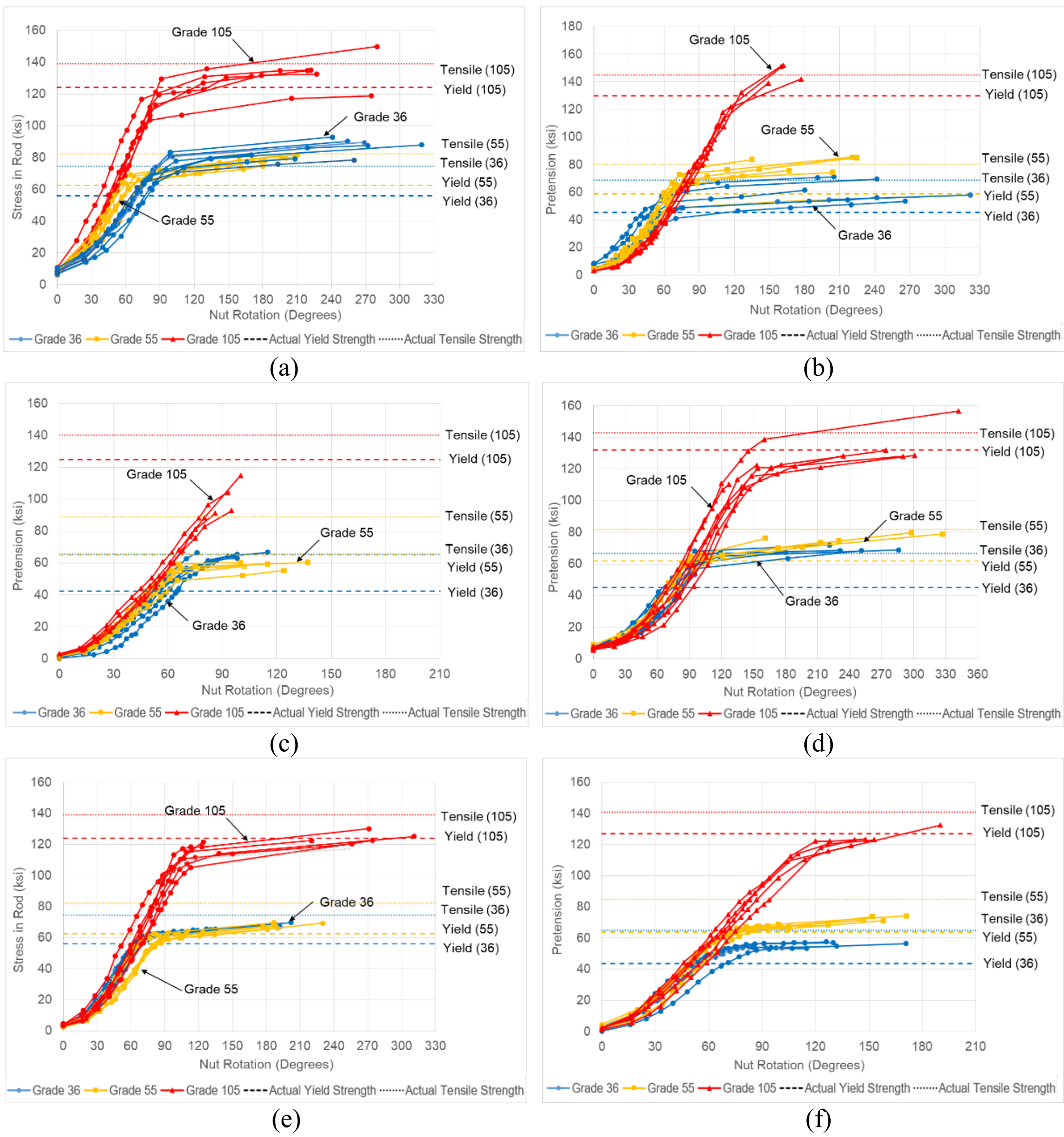

Figure 12. Combined stress vs. nut rotation curves (a) 1 inch rods and Steel Base Plate (b) 1.5 inches rods and Steel Base Plate (c) 2 inches rods and Steel Base Plate (d) 0.75 inch rods and Aluminum Base Plate (e) 1 inch rods and Aluminum Base Plate (f) 1.25 inches rods and Aluminum Base Plate

Additionally, the grade 36 rods behaved very similar to the grade 55 rods, as evidenced by the overlapping curves in Figure 12 (a) to (f). Grade 36 and 55 anchor rods behaved similarly because of the proximity in their yield strength values. The grade 105, 2 inch anchor rods did not yield during testing because of the large torque required for tightening (see Figure 12 (c)). Also, the maximum and minimum snug-tight pretension values achieved during the tightening study have been shown in Table 6 for reference.

Table 6. Maximum and minimum values of snug-tight pretension

Diameter of rod (inch)	**Base Plate**	**Snug-tight Pretension (ksi)**	
		Minimum	**Maximum**
¾	Aluminum	6	9
1		3	5
1¼		1	5
1	Steel	7	11
1½		4	9
2		1	4

Steel vs. Aluminum Base Plates

The ‘Stress versus. Nut Rotation’ curve for each of the 1 inch diameter anchor rods (both steel and aluminum baseplates) is shown in Figure 13. The similar behavior of the rods in the elastic region (approximately same initial slope) in the two baseplate types, as shown in Figure 13, indicates that the turn-of-the-nut tightening procedure and corresponding required nut rotations are independent of the material of the base plate. However, local yielding of the aluminum plate around the anchor rod hole was observed during the tightening of the grade 105 anchor rods. The FE model results also showed that the cast aluminum base would approach its minimum specified yield strength of 26 ksi close to the minimum specified yield of 105 ksi for grade 105 anchor rods.

The scatter observed in Figure 13 can be partially attributed to different grade rods from different heats.

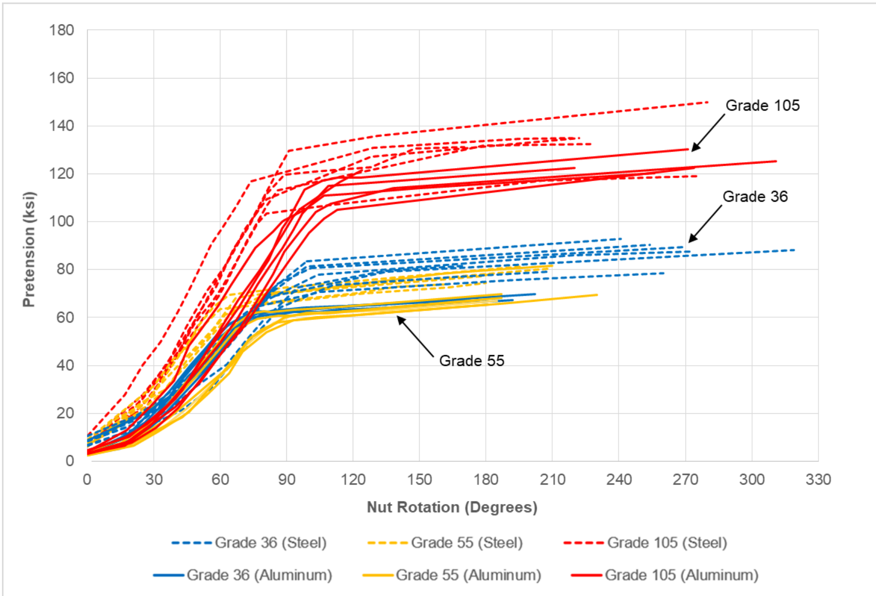

Figure 13. Stress vs. Nut Rotation curve for 1 inch diameter rods (steel and aluminum plates)

It was also observed that the anchor rods tightened on the aluminum plates required larger nut rotations for attaining the same anchor rod pretension levels as compared to the anchor rods tightened on steel plates, especially for grade 55 and 105 anchor rods (see Figure 13). The anchor rods tightened on the aluminum plate also yielded at a relatively lower value. These difference in the anchor rod behavior for the two base plate materials could be explained due to the small differences in the calibration slopes for the two base plates. However, the difference in anchor nut rotations corresponding to the minimum installation pretension values for the anchor rods tightened on the base plate materials was found to be small (~10˚) which will not have a significant effect on the overall recommendations.

3.1.6 Recommendations

The minimum pretension and nut rotation for different grades and diameters of anchor rods have been evaluated based on experimental testing conducted as part of this study. It was discussed earlier that the average pretension developed in the grade 55 – 1 inch diameter rods was approximately 45 ksi at 49˚ nut rotation. Thus, tightening a grade 55 – 1 inch diameter anchor rod 49˚ beyond snug-tight condition will produce a minimum of 45 ksi stress in the rod which is equal to 0.6 times the minimum specified tensile strength of 75 ksi. Nut rotation values, including the measured mean and two times the standard deviation (2σ), are tabulated for each of the grades and diameters of anchor rods tested in Table 7. The 2σ values account for the variation in the nut rotation values within a particular diameter and grade of the anchor rod.

Table 7. Test results for minimum pretension and nut rotation (including mean and 2σ)

Diameter of rod (inch)	**Base Plate**	**Nut Rotations beyond snug-tight (˚) Mean (2σ)**			**Minimum Pretension**		
		Grade 36	**Grade 55**	**Grade 105**	**Grade 36**	**Grade 55**	**Grade 105**
¾	Aluminum	58 (16)	77 (18)	124 (13)	$0.5\ F_u$	$0.6\ F_u$	$0.7\ F_u$
1		44 (14)	58 (14)	87 (8)			
1¼		41 (16)	57 (17)	97 (20)			
1	Steel	35 (17)	49 (21)	86 (29)			
1½		42 (15)	56 (15)	86 (8)			
2		42 (11)	56 (12)	85 (7)			

The minimum turn-of-the-nut rotations based on the mean values are tabulated in 15˚ increments for ease of tightening and verification in the field (see Table 8). The 2σ was found to be an average of 15˚ for all the rods tested. Therefore, the tolerance on the recommended values is +15˚ which allows for any over-tightening during snug-tightening or external loading.

Table 8. Recommended minimum nut rotations for turn-of-the-nut tightening in double-nut moment connections

Diameter of anchor rod (inches)	Minimum Nut Rotation beyond snug-tight (˚)			Minimum Pretension		
	F1554 Grade 36	F1554 Grade 55	F1554 Grade 105	F1554 Grade 36	F1554 Grade 55	F1554 Grade 105
< 1	60˚	75˚	120˚	$0.5\ F_u$	$0.6\ F_u$	$0.7\ F_u$
≥ 1	45˚	60˚	90˚			

3.1.7 Key Findings

Minimum installation pretension

The authors propose to tighten grade 105 rods up to 70% of the minimum specified tensile strength as opposed to 60%, which is as per the current FHWA guidelines (Garlich and Thorkildsen 2005). All the grade 105 rods that were tested in this study yielded between 100-120 ksi during the tightening, which is greater than the specified 60% value of 75 ksi. Making this change ensures P/F_y of 83% for grade 105 rods, which is consistent with the other grades of anchor rods. The current minimum pretension levels for grade 36 and 55 were examined in this study, and these rods performed well.

Grouping of Anchor Rod Diameters

There has not been extensive research in the past on tightening procedures for anchor rods with diameters less than 1.5 inch. In addition, existing AASHTO specifications (AASHTO 2015) classify nut rotations for all rods below 1.5 inch diameter under one category. Because of these circumstances, all different diameters from 0.75 inch to 2 inch were tested in this research project. Testing results showed that all the rods with diameters greater than or equal to 1 inch performed similarly to each other as opposed to diameters greater than 1.5 inch currently specified (see Table 8). Therefore, the authors propose to change the grouping of the anchor rod diameters to less than 1 inch and greater than or equal to 1 inch as per the test results.

Separate Nut Rotations for Grade 55 and 105

Separate minimum nut rotations have been recommended for grade 55 and 105 rods in Table 8, whereas the present FHWA guidelines (Garlich and Thorkildsen 2005) and AASHTO specifications (AASHTO 2015) categorize grade 55 and 105 rods in the same group. In the FHWA guidelines, grade 55 rods and 105 rods have a minimum pretension level of $0.6*F_u$ (45 ksi) and $0.6*F_u$ (75 ksi), respectively. According to this research, grade 105 anchor rods need to be tightened at least 30˚ greater than grade 55 anchor rods to achieve the desired minimum pretension levels. Therefore, both the grades cannot be tightened to the same nut rotation or categorized in the same group.

Observed over-tightening and under-tightening

The revised recommended nut rotation values corresponding to the minimum installation pretension shown in Table 8 were compared to the currently specified nut rotation values in the AASHTO tightening specifications shown in Table 2 to observe any instances of over-tightening and under-tightening as per the current specifications (see Table 9). From the comparison, it was found that the grade 55 rods (≤ 1.5 inch diameter) were being over-tightened by 45˚-60˚ on average. These rods are required to be tightened to 120˚ as per the current AASHTO specifications but the test data showed that 60˚-75˚ nut rotation beyond snug-tight is sufficient for achieving the required minimum installation pretension. Also, grade 105 rods (> 1 inch and < 1.5 inch) were observed to being over-tightened by 30˚. The observed nut rotation for grade 105 rods (> 1.5 inch diameter) was 90˚ as opposed to the recommended 60˚. However, grade 36 anchor rods showed a variation of only 15˚ which is within the recommended tolerance or two standard deviations of the mean. Summarized results of over-tightening and under-tightening are shown in Table 9.

Table 9. Anchor rod diameters over-tightened or under-tightened

Anchor Bolt Diameter (inch)	Over tightened (O) or Under tightened (U)		
	Nut rotations in parentheses		
	Grade 36	Grade 55	Grade 105
< 1	-	O (45˚)	-
≥ 1 and ≤ 1½	O (15˚)	O (60˚)	O (30˚)
> 1½	U (15˚)	-	U (30˚)

Snug tight and grip length

According the tightening procedures specified in AASHTO, the snug-tight condition is defined as the maximum nut rotation resulting from the full effort of one person using a 12 inch long wrench or equivalent (AASHTO 2015). However, FHWA guidelines (2005) and NCHRP 469 (2002) define snug-tight pretension as 20% to 30% of the final pretension. There is no universally accepted definition of snug-tight condition. Snug-tight pretension is highly variable due to different wrench lengths and the interpretation of the definition. Previous research on nut loosening in high-strength bolts (Nassar and Matin 2006) and anchor rod connections (Hoisington and Hamel 2016) has shown that nut loosening can occur as a result of post-yield loading due to external wind-loads and overtightening. Overtightening during snug-tightening in combination with large verification torque values has been found to be partially responsible for the yield of anchor rods (Hoisington et al. 2014).

One of the methods that can reduce the variability associated with snug-tight pretension is by using specified wrench length or snug-torque for a snug-tightening a particular diameter and grade of anchor rod. However, this area needs further research. Snug-tight stress ranging from 1-10 ksi was observed during tightening procedures in this research study. The recommendations in this study are based on these snug-tight pretension values, and it is believed that the tolerance of +15˚ should allow for over-tightening during snug-tightening if any. Base plate thickness (or the grip length) equal to the diameter of the rod was chosen in this study. Varying grip lengths for a particular diameter of the rod was not considered because of the common industry practice of specifying base plate thicknesses of similar dimension to the rod diameter. Also, according to Chen et al., the grip length effect is only significant when the base plate thickness (or the grip length) is more than double than the diameter of the rod.

3.1.8 Conclusions

There were differences between nut rotation recommendations in the current specifications and the results from this research. As a result, the following conclusions have been made:

1. Current specifications require a minimum pretension of 0.6 times the minimum specified tensile strength for grade 105 rods. This value has been recommended to be increased to 0.7 times as per the testing in this research project. Increasing the factor from 0.6 to 0.7 ensures P/F_y of 83% for grade 105 rods, which is consistent with the other F1554 grades.
2. Anchor rod diameters greater than 1 inch performed similarly to each other. Therefore, the recommended two categories of anchor rod diameters are less than 1 inch, and greater than or equal to 1 inch. These two categories are different from the current specifications, which group all rods with diameters greater than 1.5 inch in one category.
3. Present tightening specifications recommend the same amount of nut rotations for grade 55 and 105 anchor rods depending on the diameter of the rods. It was observed during this study that this specification leads to inadequate tightening of grade 105 larger diameter rods (> 1.5 inch diameter). It also leads to yielding of grade 55 rods (< 1.5 inch diameter)

and grade 105 rods (> 1 inch and < 1.5 inch). This research recommends separate nut rotation specifications for grade 55 and 105 rods to ensure proper tightening of the rods.

4. Grade 36 anchor rods (> 1 inch) were found to be under-tightened or over-tightened by 15° which is within the recommended tolerance limit. This relatively small rotation can be hard to control while tightening in the field and does not change the results in a statistically significant way.
5. One inch diameter anchor rods performed similarly on the steel and aluminum base plates. Therefore, it was concluded that the turn-of-the-nut procedure and recommended nut rotations are independent of the material of the base plate.

3.2 Tightening Procedures for single-nut moment connections inside a Transformer Base (T-base) pole

3.2.1 Introduction

T-base poles and most of the aluminum ancillary structures consist of single-nut connections at the base. T-base poles are commonly used for aluminum luminaires. The aluminum pole is welded to a cast-aluminum shoe base, and the shoe base is fastened to the T-base using structural bolts. A typical T-base pole connection is shown in Figure 14. There are no prescribed separate guidelines for tightening single-nut connections on ancillary structures. At present, NCHRP 469 recommends tightening single-nut connections to the same pretension as double-nut moment connections (Dexter and Ricker 2002). Also, AASHTO recommends tightening single nut connections on ancillary structures to half of the nut rotations recommended for double nut connections (AASHTO 2015). There is also no guidance regarding tightening of single-nut connections provided in the VDOT Road and Bridge Specifications (VDOT 2016a).

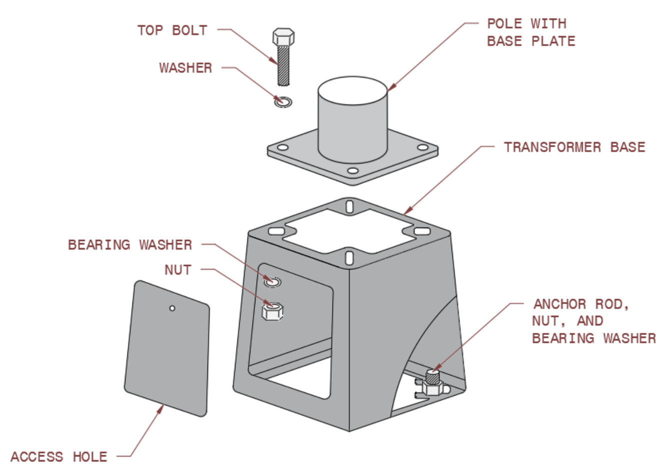

Figure 14. A luminaire with a T-base connection (left) and components inside a T-base (right)

Breakaway aluminum transformer bases are designed so that they “break away” from the rest of the unit when hit with a certain amount of vehicular force. Single-nut tightening procedures are not followed for tightening anchor nuts inside a T-base. Instead, breakaway T-bases generally come with manufacturer's instructions for installation. Most of the breakaway T-bases require the anchor rods to be torqued to 150-200 ft-lbs instead of using the turn-of-the-nut procedure (see Figure 15). As seen in Figure 15, it can be challenging to tighten anchor nuts using a hydraulic wrench or torque wrench inside the transformer base due to limited access and a high amount of electrical wiring. The structural bolts connecting the pole/shoe base to the T-base may be required to be tightened using the turn-of-the-nut method as per the shop drawings.

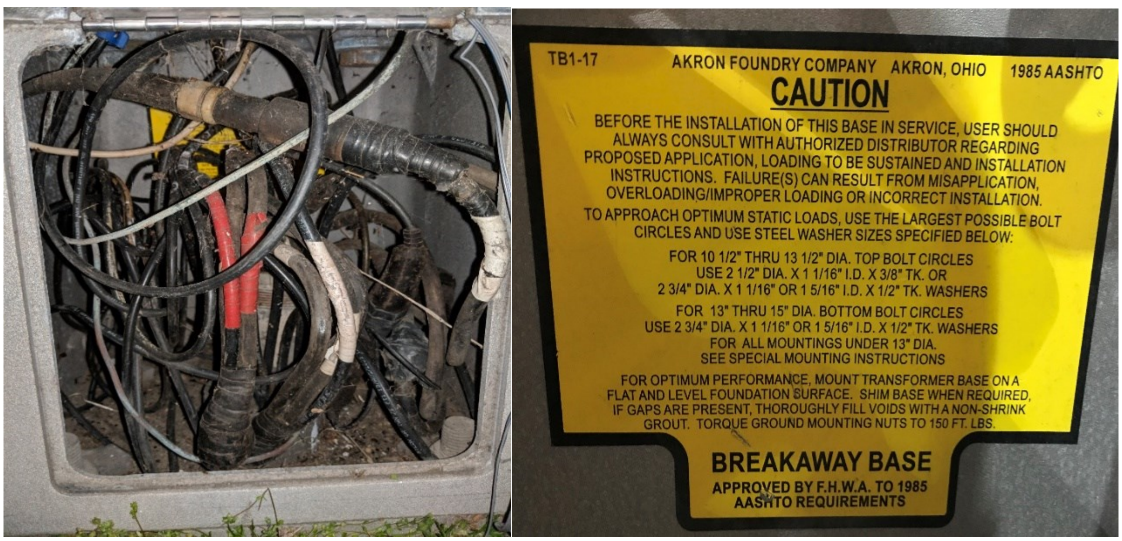

Figure 15. Electrical wiring (left) and manufacturer's instructions for installation (right) inside T-base

Due to the lack of specific tightening procedures related to T-bases, a tightening study on anchor rods of the T-base connection was conducted. The tightening study was performed in order to evaluate the relationship between applied torque, nut rotation, and pretension in the anchor rod. Since these connections are typical single-nut connections for aluminum ancillary structures, the results were used for developing tightening procedures for single-nut connections in general. A survey of pole manufacturers, installation crews, and DOT personnel across the state of Virginia was conducted to identify any potential good tightening methods used at present across the state of Virginia (See Appendix A for survey results). Further, some of the good tightening methods (deep sockets and long extensions) identified from the survey were used to perform the tightening study on a T-base in the laboratory.

3.2.2 Test-setup

Four 1-inch, grade 55 anchor rods were cast inside a 30-inch diameter concrete foundation. The typical detailing given in the VDOT 2016 Road and Bridge Standards was followed (VDOT 2016b). The foundation was 24 inches deep. The anchor rods were surrounded by a rebar cage consisting of 12-#8 vertical rebar and 5-#4 rebar ties at 4.5 inches on center. The concrete foundation was connected to a 1-inch thick A36 grade steel plate using (4) 0.75-inch diameter steel stud anchors. The plate was further fastened to the strong floor of the laboratory. The formwork before placing of concrete and the final test-setup is shown in Figure 16.

Figure 16. Formwork for the concrete foundation (left) and T-base with the casted foundation (right)

3.2.3 Instrumentation

Fifty-kip through-hole load cells (Transducer Techniques model: THD-50K-Y) were used to measure the pretension in the anchor rods. A manual calibrated torque wrench (CDI model:

4504MFRMH) with a torque capacity of 450 ft-lbs was used for tightening the anchor rods incrementally onto the T-base. Deep sockets along with extensions were also used for the ease in tightening, as concluded from the survey comments. The through-hole load cells were initially calibrated in compression using a 400 kip capacity compression testing machine (Forney model: QC50DR). During tightening, the change in nut rotation was recorded visually using an 180˚ radial gauge. A Campbell Scientific datalogger was used for monitoring and recording pretension data.

3.2.4 Test Procedure

Each of the four anchor rods was tightened five times in total using two tightening techniques. The first technique involved tightening the anchor rod using a 3-inch deep socket from the access hole of the T-base (see Figure 17). The second technique involved tightening the anchor rod using the 3-inch deep socket along with a 16-inch long extension. For ease of tightening, the extension was passed through the upper holes for structural bolts (see Figure 17).

Figure 17. Tightening through the access hole (left) and tightening using the extension from the top (right)

Both tightening techniques were evaluated for ease and effectiveness. The effect of lubrication (beeswax) on applied torque, pretension, and ease of tightening was also evaluated during each technique. Each anchor rod was tightened with and without lubrication using the two tightening methods. Finally, each lubricated rod was tightened above the yield strength of the anchor rod using the long extension tightening technique. Each test involved tightening the anchor rod in torque increments and recording the corresponding pretension and nut rotations.

3.2.5 Results

Yield and Tensile Strength

Grade 55 anchor rods were used for the tightening study. The actual yield strength and tensile strength of the anchor rods, according to the mill certification documents, were 62.3 ksi and 84.2 ksi, respectively.

Comparison of Tightening Techniques

As discussed in the test procedure section, the anchor nuts on the T-base were tightened using two techniques. The first technique involved using a 3-inch deep socket along with a torque wrench positioned through the access hole in the front of the T-base. The process presented a challenge in tightening the rods due to the lack of clearance for tightening and limited access while tightening. The second technique involved using a 16-inch vertical extension along with the deep socket and torque wrench. The long extension was passed through the bolt holes on the top of T-base. This technique proved to be relatively easier when tightening the rods since there was clearance to rotate the torque wrench 360˚.

It was also observed that there was a better distribution of stresses in the anchor rods when the tightening was performed incrementally in a star pattern, as shown in Figure 18. For example, if the target torque is 300 ft-lbs, tightening should be done in four increments of 75 ft-lbs, following the star pattern each time.

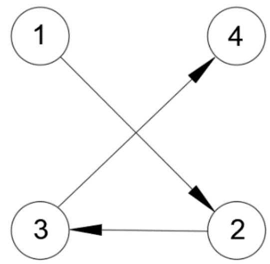

Figure 18. Star pattern for tightening of 4 anchor rods

Unlubricated Rods

The effect of lubrication on pretension, applied torque, and the ease of tightening was also examined. The pretension vs torque relationship for both lubricated and unlubricated anchor rods is shown in Figure 19. The average slope for the unlubricated rods was shallower than the average slope for the lubricated rods. This suggests that it took a larger amount of torque to tighten the unlubricated rods as compared to the lubricated rods; therefore, it can be concluded that lubrication facilitates the tightening process and makes it easier to achieve the desired pretension at relatively lower levels of torque.

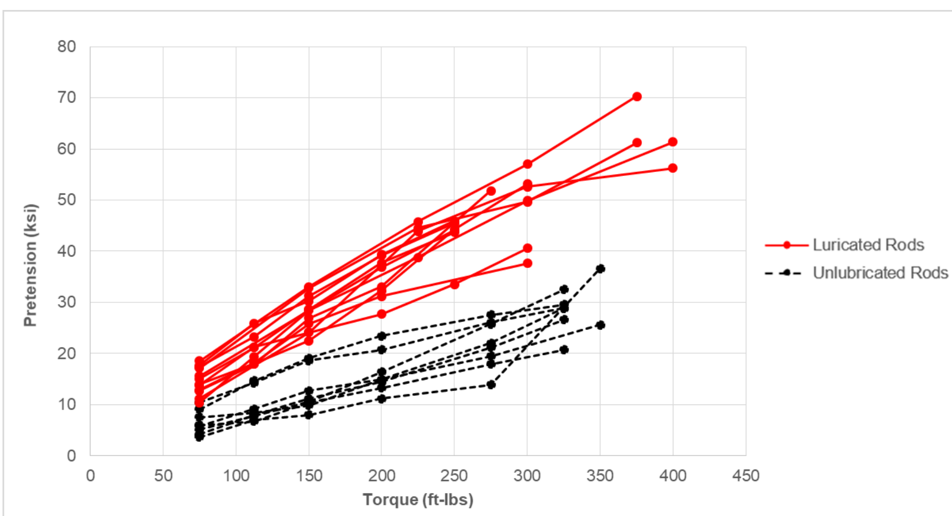

Figure 19. Comparison of pretension vs torque relationship between lubricated and unlubricated rods

Lubricated Rods

The pretension vs torque relationship for the lubricated anchor rods is shown in Figure 20. All four of the anchor rods behaved similar to each other. There was no significant change in slope of the curves and, hence, the curves were not indicative of the yielding of the anchor rods. On average, it took approximately 260 ft-lbs of torque to achieve 0.6*F_u (45 ksi) of pretension in the anchor rods (see Figure 20). It was determined that the recommended torque value of 150-200 ft-lbs for T-bases would only produce 25-35 ksi of pretension in the anchor rods, which is almost half of the yield strength (55 ksi). Previous research shows that single-nut connections lose pretension quickly under dynamic loads due to concrete wear under the T-base or the base plate (Dexter and Ricker 2002). Therefore, it is necessary to pretension these connections as much as possible without yielding the anchor rods.

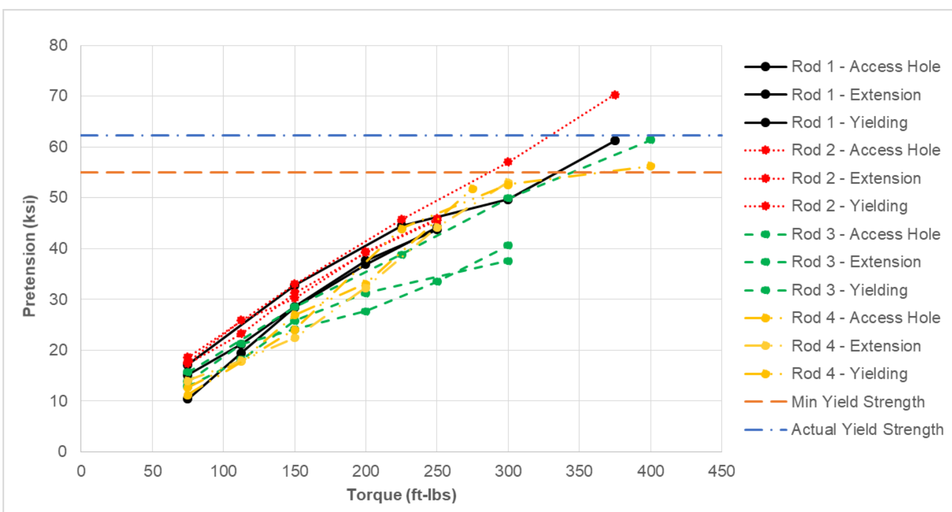

Figure 20. Pretension vs torque curve for lubricated rods

The pretension vs nut rotation curves for all of the tested rods are shown in Figure 21. There was more scatter observed in the nut rotation curves as compared to the torque curve. This could be due to the slipping of the nut on the bearing surface of the load cell as well as the uneven surface of the concrete below the T-base. The yielding of the rods due to the change in slope was more clearly observed in the nut rotation curves. The yielding of the rods or change in slope was observed near the specified minimum yield strength of 55 ksi (see Figure 21). On average, the mean nut rotation corresponding to 0.6*F_u (45 ksi) of pretension in the anchor rods was found to be 65˚.

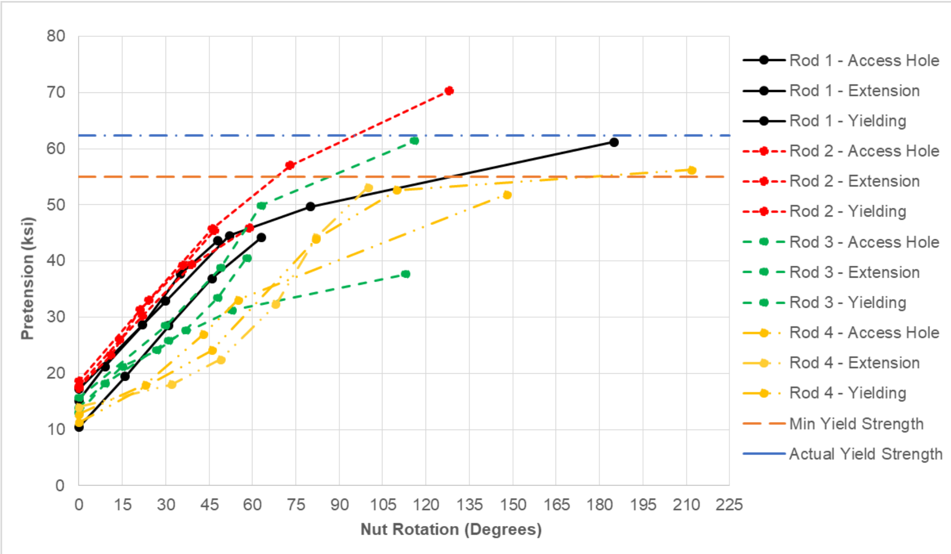

Figure 21. Pretension vs nut rotation curve for lubricated rods

3.2.6 Observations and Findings

1. It is very tedious and time consuming to measure nut rotations inside the T-base. Hence, it is recommended to use torque instead of the turn-of-the-nut method for tightening single-nut connections on T-bases.
2. If the turn-of-the-nut method is followed, 60˚ of nut rotation would be enough to produce 45 ksi of pretension in grade 55 anchor rods.
3. The manufacturer recommended value of 150-200 ft-lbs of torque produces only 25-35 ksi of pretension in single-nut connections on T-bases. A larger torque value (250 ft-lbs) would allow for proper tightening of lubricated grade 55 anchor rods on T-bases and single-nut connections without yielding the rod.

4. Lubrication facilitates the ease of tightening. Therefore, the anchor rods, nuts, and all bearing surfaces should be lubricated with beeswax before tightening.
5. It is challenging to tighten the anchor nuts inside of the T-base. The tightening of anchor rods from the top of T-base using a long vertical extension along with deep sockets helps to reduce the effort and time involved with tightening.
6. The anchor nuts should be incrementally tightened in a star pattern for better distribution of stresses in the anchor rods.

3.3 Revised Tightening Specifications for Anchor Rods in Ancillary Structures.

A revised tightening procedure for double-nut moment connections incorporating changes to current specified nut rotation values in the AASHTO specifications along with other measures to prevent improper tightening has been proposed as shown in Appendix B (AASHTO 2015). A new tightening procedure for single-nut connections with grade 55, 1-inch anchor rods in ancillary structures has also been specified in Appendix B. The tightening procedure for single-nut connections includes tightening instructions for both T-base poles and poles with an aluminum cast shoe.

CHAPTER 4: Field Monitoring

Chapter 4 was not part of any manuscript and contains a detailed description of the results from a four month field monitoring program performed on two ancillary structures – one galvanized steel and one aluminum luminaire.

4.1 Literature Review

Previous field monitoring studies on high-mast lighting poles (HMLP) (Connor et al. 2012; Connor and Hodgson 2006; Hamel and Hoisington 2014; Phares et al. 2007) were focused on a better understanding of the dynamic performance of HMLPs under wind-induced vibrations. Some of the studies investigated the loosening of anchor nuts (Hamel and Hoisington 2014), whereas others focused on looking at fatigue failures/limit states due to wind-induced vibrations (Connor et al. 2012; Connor and Hodgson 2006; Phares et al. 2007).

The field monitoring data from the University of Alaska research study were indicative of the role of foundation type and the number of anchor rods in the anchor nut loosening (Hamel and Hoisington 2014). The study also found that the snug tight torque and grip length/rod diameter ratio influenced the pretension in the rod. In 2012, Connor et al. concluded that HMLPs were susceptible to vortex shedding in the second and third modes, and are required to be designed for infinite fatigue life. In another research study, stresses as high as 12.4 ksi in the first mode were observed due to high-wind speeds during field monitoring (Phares et al. 2007). However, the cumulative frequency of occurrence of wind speeds greater than 20 mph causing high stresses was small (< 5%).

All of the long-term monitoring programs addressed in this literature review involved instrumentation of sensors like anemometer (wind monitor) for measuring wind speeds/direction, accelerometers for measuring wind-induced vibrations, and foil/bolt strain gages for measuring induced stresses on the structures. The sensors were typically connected to a data acquisition system (see Figure 22). In some cases, dynamic behavior of the structures (natural frequency and modal damping ratios) was predicted using pluck tests (pull tests) in the field.

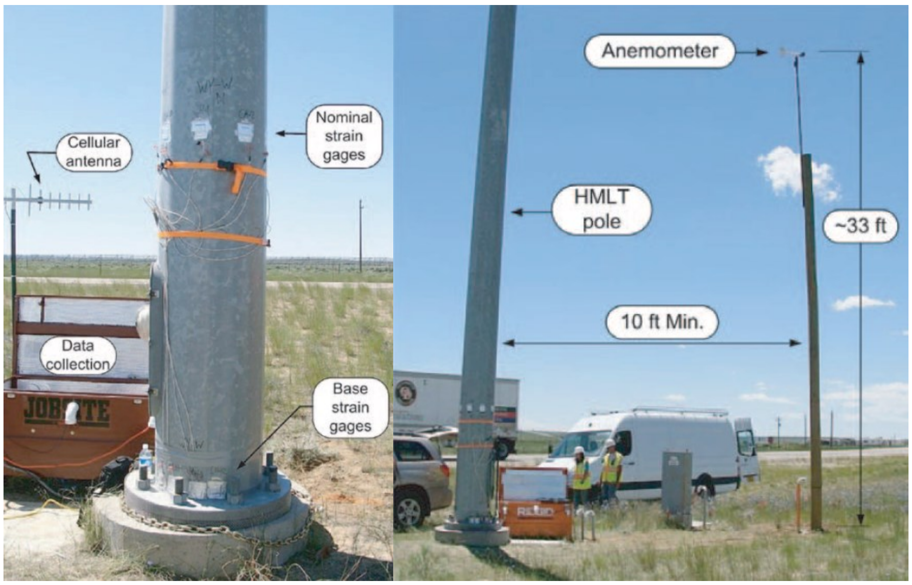

Figure 22. Strain Gage locations, anemometer and DAQ system (Connor et al. 2012). Reproduced with permission from the National Academy of Sciences, courtesy of the National Academies Press.

Other ancillary structures, like variable message signs (VMS), highway luminaires, and cantilevered sign structures, have also been monitored (Foutch et al. 2006; McLean et al. 2004; Zuo and Letchford 2008). In one study, vibration mode 1 was caused by natural gusts (buffeting) and vibration mode 2 was observed due to vortex shedding during the long-term monitoring (Zuo and Letchford 2008). Foutch et al. also concluded that resonant vibrations were the main cause of fatigue cracking in highway sign truss members.

In some field monitoring studies, multiple accelerometers have been used along the height of the structure to capture multiple modes of vibrations seen in the field (see Figure 23). The latest technologies, such as infrared cameras, were also used for measuring and validating deflections with the analytically calculated deflections from accelerations in a recent study (Zuo and Letchford 2008). In general, the setup for long-term monitoring consisted of sensors, a data acquisition system, video/digital cameras, a wireless modem, an antenna, and a job-box (see Figure 24).

Figure 23. The instrumentation on the forty feet aluminum pole (Zuo and Letchford 2008). Reproduced with permission from the author.

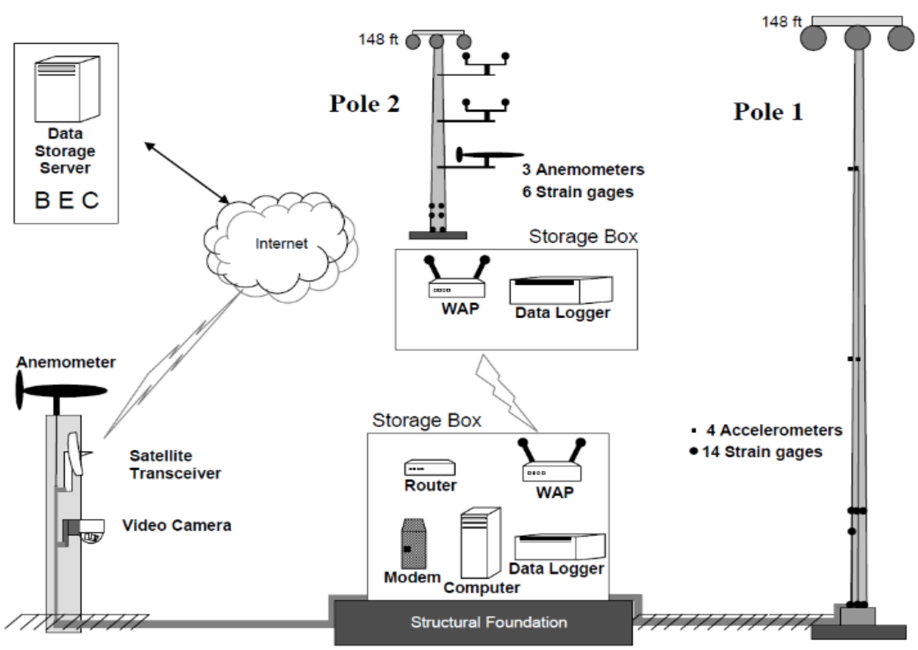

Figure 24. The general setup for long-term field monitoring (Phares et al. 2007). Reproduced with permission from the author.

Similar to the past field monitoring programs performed on ancillary structures, a field monitoring study was conducted prior to large-scale testing to identify the dynamic characteristics of a galvanized steel traffic signal and an aluminum luminaire. The long-term stress and acceleration data collected from the field monitoring program were further used for simulating wind-induced vibrations on a full-scale ancillary structure.

4.2 Introduction

Two ancillary structures were instrumented and monitored for four months in a high wind speed region near the east coast of Virginia. Two different structure types—one aluminum luminaire and one overhead galvanized steel traffic signal located near the James River Bridge in Carrollton, Virginia, were field monitored from April 2018 to July 2018 (see Figure 25). The structures were instrumented with accelerometers, a wind monitor, and strain gages. The sensor data history was collected using a data acquisition system over the four months and used to analyze and determine observed vibration loads and stress ranges on these structures relative to specific wind speeds and wind direction. Similar loading conditions were simulated in the large-scale experimental testing program. The other purpose of the field monitoring was to determine the dominant modal frequencies and the structural behavior under vibrations.

Figure 25. Instrumented luminaire and traffic signal near the east coast of Virginia

4.3 Field Tests

Pluck tests were performed on the individual poles to quantify their dynamic characteristics (see Figure 26). Pluck tests were conducted by pulling the top of the poles laterally using an instrumented cable. One end of the cable was tied to the top of the pole using a sling, and the other end was tensioned using a come-along attached to the trailer hitch. The cable was released using a quick-release shackle. Pluck tests were done to induce free vibrations in the poles. The resulting vibration data was further used to calculate the natural frequencies and damping ratios of each of the modes of the two poles.

Figure 26. Pluck test performed on the overhead traffic signal

Two pluck tests each were performed along the in-plane and out-of-plane directions of the cantilever mast-arm of each of the poles. The in-plane and out-of-plane directions have been denoted as Y-direction and Z-direction, respectively, in this report. After the pluck tests, poles were remotely monitored for ambient wind vibrations for a period of four months. In order to collect the required data, the data acquisition system was programmed to collect data only when the wind speed exceeded trigger levels as set during the long-term monitoring.

4.4 Instrumentation

4.4.1 Wind Monitor

A propeller-type anemometer (Model 05103: RM Young Company) was instrumented on top of the light pole for recording wind speeds and wind direction. The wind monitor was mounted on top of an 8-foot aluminum pipe, which was clamped to the top of the 25-foot light pole. Therefore, wind speeds and direction were measured at the height of approximately 33 feet above the ground, which is the standard height used for wind speed computations in ASCE and AASHTO specifications.

4.4.2 Accelerometers

One tri-axial MEMS DC accelerometer (Model 3713E1125G: PCB Piezotronics, Inc.) was instrumented on top of each of the two poles for measuring the amplitude and frequency of accelerations due to wind forces. According to previous research, these types of poles vibrate with low amplitude and low-frequency accelerations due to winds (Connor and Hodgson, 2006). Therefore, accelerometers capable of measuring frequencies (0-1500 Hz) and acceleration amplitudes (±25 g peak) were used.

4.4.3 Strain gages and Thermocouple

Eight temperature compensated strain gages (Model CEFLA: Tokyo Measuring Instruments Laboratory Co., Ltd.) were installed on each pole near the base plate to record the stresses corresponding to the wind forces. The strain gages were installed 45˚ apart to measure the bending stresses induced due to pluck tests and ambient wind vibrations. The strain gages were installed two feet above the base plate of the luminaire and two feet above the hand-hole of the traffic signal to avoid any stress risers due to sharp geometric discontinuities around the hand-hole or base plate. A K-type thermocouple (Omega Engineering) with a separate data logger was also installed near the job-box to measure the change in temperature of the ambient conditions every 5 minutes throughout the duration of the field monitoring. The instrumented sensors are shown in Figure 27.

Figure 27. Wind monitor (left), Accelerometer (center), and Strain Gages (right)

4.4.4 Data Acquisition

A CR5000 data logger from Campbell Scientific, Inc. was used for recording data and remote monitoring. The data-logger was a 16-bit data acquisition system with 20 differential and 40 single-ended analog channels. Sixteen strain gages, two accelerometers, and a wind-monitor were connected to the CR5000 data acquisition system. The CR5000 data logger was further connected to a cellular modem (Sierra Wireless Raven X) for wireless communications through a satellite internet connection. The data logger was constantly powered through three universal 12-volt, 200Ah batteries connected in parallel (as seen in Figure 28). The batteries were charged by a 7.5A–12V smart battery charger for approximately 8 hours each night where external power was supplied to the luminaire circuit. The sensors, batteries, data acquisition system, and modem were enclosed in a weather-proof job-box at the site.

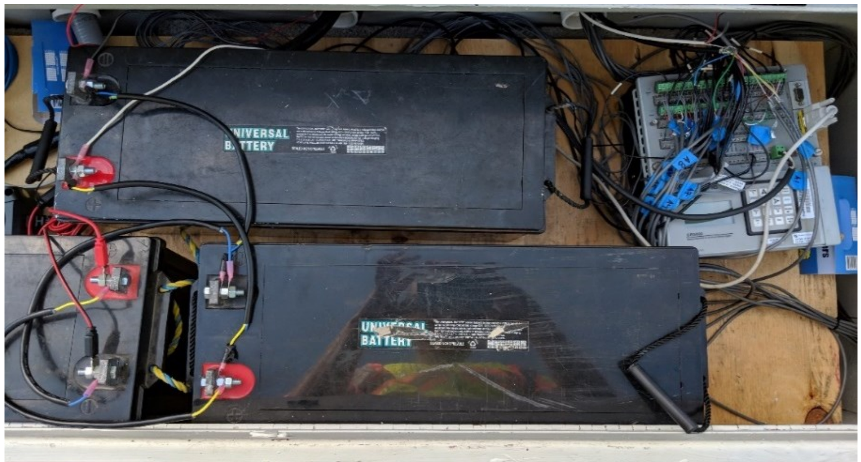

Figure 28. Parallel battery connection for charging CR5000

The accelerometer and the strain gage data were collected at a frequency of 50 Hz, whereas wind data were recorded at a lower frequency of 2 Hz. Fifty Hz frequency was chosen to ensure that the frequencies equal to or less than the Nyquist frequency (25 Hz) would be easily observed in the data without the effect of aliasing. As per previous studies, it was expected that at least three modal frequencies within 25 Hz for these poles would be observed. Data signal processing was performed using a commercial data analysis and graphing software Origin Pro 2017 (OriginLab Corporation). The accelerometer and strain gage data were filtered through a sixth-order bandpass Butterworth filter with the cut-off frequencies set at 0.5 Hz (≤ half of the fundamental frequency of the poles in each direction) and 25 Hz (Nyquist frequency).

4.5 Results

4.5.1 Modal Frequencies

Two pluck tests were conducted along each of the in-plane and out-of-plane directions of the cantilever mast-arm of the poles. Precautions were taken so that no traffic-induced vibrations (e.g. gusts from passing vehicles) occurred during the pluck tests. The in-plane and out-of-plane directions have been denoted as the Y-direction and Z-direction in the results, respectively. The filtered acceleration data in the time domain of each direction was converted into the frequency domain using a Fast Fourier Transform (FFT) analysis. Peaks in the frequency spectrum were used to identify the first few natural modal frequencies of the poles in the Y and Z directions. Acceleration time history along with the frequency spectrum for pluck test 1 in the Y direction performed on the traffic signal and luminaire are shown in Figure 29 and Figure 30, respectively.

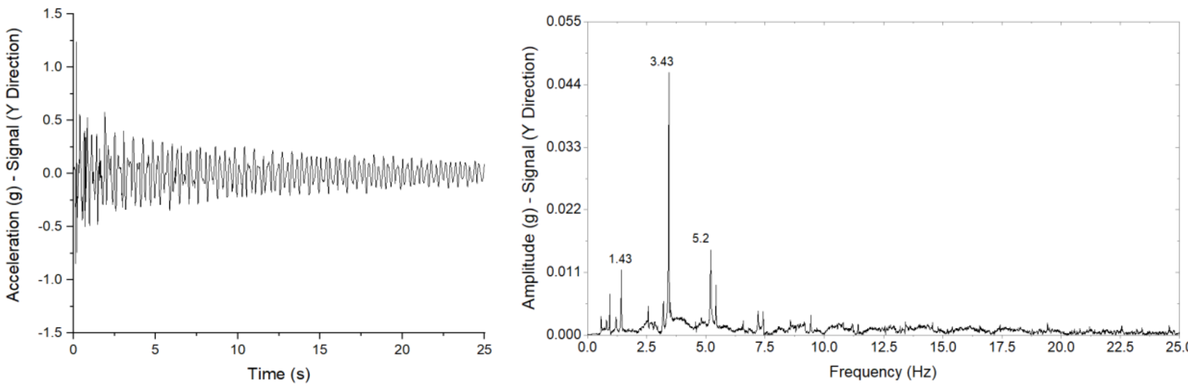

Figure 29. Acceleration time history (Left) and frequency spectrum (Right) for the pluck test 1 performed on signal in Y direction

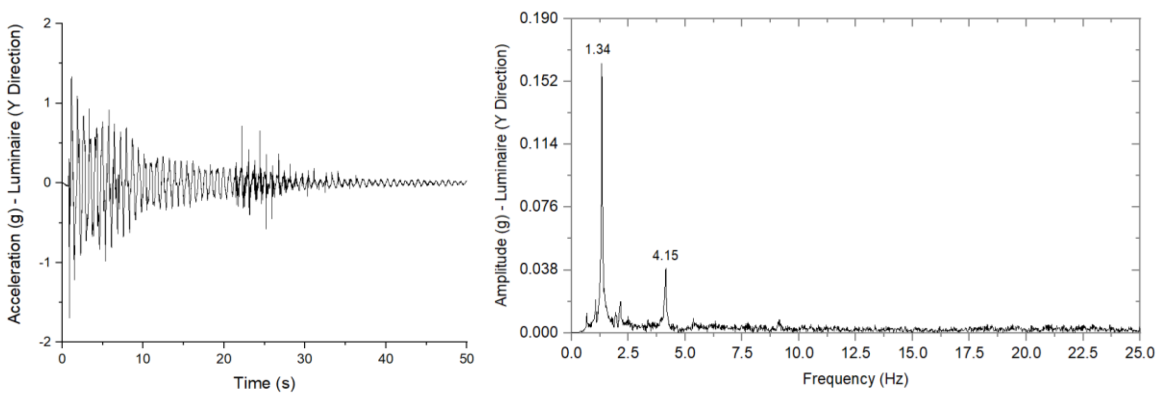

Figure 30. Acceleration time history (Left) and frequency spectrum (Right) for the pluck test 1 performed on luminaire in Y direction

The modal frequencies for the traffic signal and the light pole from the FFT analysis are compiled in Table 10 and Table 11, respectively. The frequencies highlighted in the tables are the observed dominant frequencies with maximum contribution during the pluck test. Although the poles were pulled at the top, multiple modes were excited due to the multi-direction vibrations induced in the cantilever mast-arms of each pole.

Table 10. Modal Frequencies for the Traffic Signal

Pluck Test	Direction	Traffic Signal - Modal Frequencies (Hz)		
		Mode 1	Mode 2	Mode 3
1	Y	1.43	3.43	5.2
2		1.42	3.41	5.18
1	Z	NA	3.48	5.76
2		1.48	3.47	5.76

Shaded numbers represent the dominant modal frequencies

Table 11. Modal Frequencies for the Luminaire

Pluck Test	Direction	Light Pole - Modal Frequencies (Hz)	
		Mode 1	Mode 2
1	Y	1.34	4.15
2		1.35	4.08
1	Z	1.04	2.75
2		1.04	2.75

Shaded numbers represent the dominant modal frequencies

4.5.2 Damping Ratios

The half-power bandwidth method was used to calculate the damping ratios for each dynamic mode of the two structures. Amplitude vs frequency curves from the FFT analysis of the pluck tests were analyzed for this purpose. It was challenging to determine the damping ratios using the half-power bandwidth method from the ambient data because of scatter around the modal frequencies. Therefore, only the data from pluck tests were analyzed. Moreover, the damping ratios calculated here include only contributions from structural damping and not aerodynamic damping. Aerodynamic damping is mainly observed when the structure vibrates in the air due to ambient winds. However, the positive/negative contribution of aerodynamic damping is generally minimal compared to the structural damping (Kijewski and Kareem, 2001). Half-power frequency points are defined as the frequency points (f_1 and f_2) having an amplitude value equal to peak value divided by $\sqrt{2}$ (Figure 31). Half-power frequency points were determined on either side of the peak (modal) frequency and the damping ratios were calculated using Equation 3. Half-power bandwidth method does not yield accurate results when the modal frequencies are close to each other. However, half-power bandwidth method worked fine for calculating modal damping ratios in this research study since the modal frequencies were spread out.

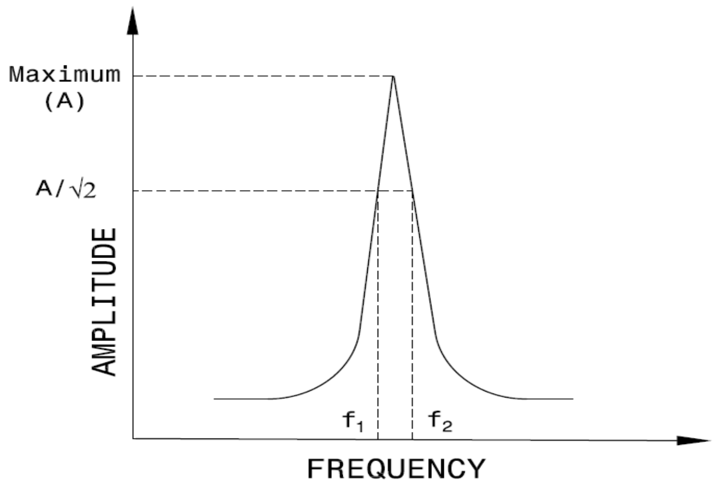

Figure 31. Half-power Bandwidth method

$$\xi = \frac{f_2 - f_1}{f_1 + f_2}$$

Equation 3. Damping ratio formula from Half-power Bandwidth method (Connor et al. 2012)

The damping ratios calculated for the traffic signal and the luminaire using the bandwidth method are shown in Table 12 and Table 13, respectively. The modal frequencies identified by the peaks in the FFT analysis were also verified with the model frequency formula $(f_1+f_2)/2$ from the half-power bandwidth method. The damping ratio for the first mode was generally found to be more than the higher modes for the traffic signal and the luminaire. The damping ratio for the traffic signal was in the range of 0.13% to 0.6%, whereas the ratio was in the range of 1.04% to 2.38% for the luminaire. A similar observation was made in the field during the pluck tests where the traffic signal took a relatively longer time to damp out the vibrations after the pluck tests as compared to the luminaire, which could be explained due to the long cantilever mast-arm of the traffic signal.

Table 12. Damping Ratios for each mode of the traffic signal

Pluck Test	Direction	Traffic Signal - Damping Ratios		
		Mode 1	Mode 2	Mode 3
1	Y	0.4	0.15	0.27
2		0.6	0.34	0.31
1	Z	NA	0.24	0.29
2		0.3	0.13	0.33

Table 13. Damping Ratios for each mode of the luminaire

Pluck Test	Direction	Light Pole - Damping Ratios	
		Mode 1	Mode 2
1	Y	1.04	0.65
2		1.56	0.87
1	Z	2.38	2.31
2		1.81	1.64

4.5.3 Ambient Wind Data

A wind monitor was installed on April 30, 2018, 25 days after the strain gage and accelerometer instrumentation. The average and maximum wind speed data were collected every day until August 4, 2018, and the wind speed variation is shown in Figure 32. There is no data for a few days on the graph because the wind speed was below the set trigger speed on those days. The average wind speed was found to be close to the different wind triggers set at 6, 10, and 15 mph regularly throughout the field monitoring (see Figure 32). A maximum wind speed of 46.9 mph was observed on May 10. Aside from this, three other major high wind speeds were 39.0 mph, 34.2 mph, and 32.9 mph. On average, the maximum daily wind speed was found to be between 15 and 25 mph. The most dominant wind speed was in the range of 9 mph-12 mph. The majority of the wind flow was from the southwest (SW) direction (~ 30%), as shown in the wind rose diagram in Figure 33. The SW direction was the same as the Z direction with respect to the orientation of the poles.

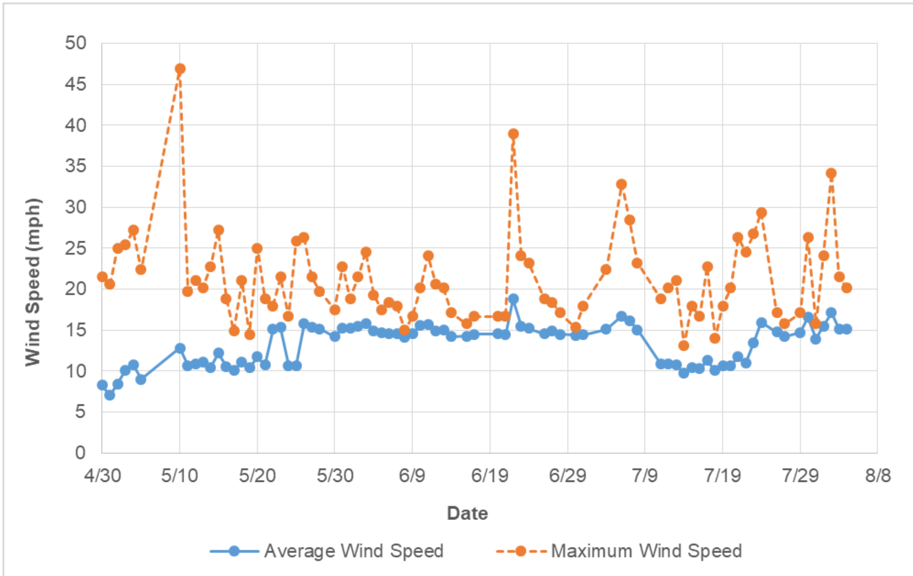

Figure 32. Average and maximum wind speed variation

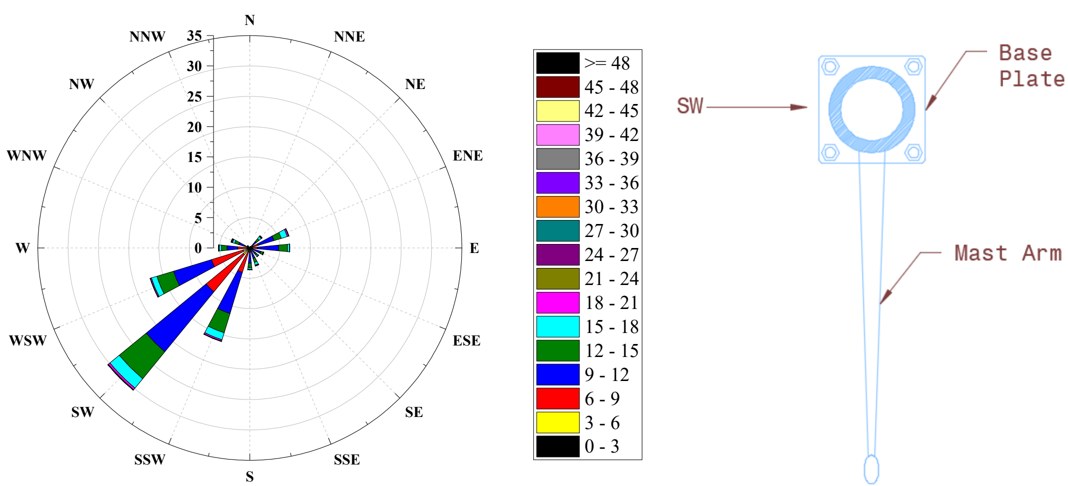

Figure 33. Wind Rose Diagram

4.5.4 Ambient Acceleration Data

FFT analyses was also performed on the ambient acceleration data to verify the modal frequencies of the structures calculated from the pluck tests. This was done since the ambient data resulted in a higher number of frequency response points and, therefore, a higher level of accuracy. The first three modes of vibration were easily observed from the FFT analysis of the daily ambient acceleration data of the traffic signal. Higher modes were not excited due to low frequency wind-induced vibrations. The second mode was found to be the most common and dominant mode for the traffic signal per the FFT analysis. Moreover, the third mode had a relatively higher contribution compared to the first mode. FFT analysis of the daily ambient acceleration data of the luminaire showed only the first two modes of vibration. Both were equally dominant with their amplitudes close to each other.

The maximum daily acceleration values of the traffic signal and luminaire due to vibrations for the four months from April to July are shown in Figure 34 and Figure 35, respectively. Peak accelerations as high as 1.8g were observed for both the structures (see Figure 34 and Figure 35). However, such peak values were observed for a very small duration (a few isolated peaks at a sampling frequency of 50 Hz or 0.02 second) during the whole day. Therefore, it is more appropriate to say that peak accelerations were commonly in the range of 0.1-0.6g for the signal and the luminaire.

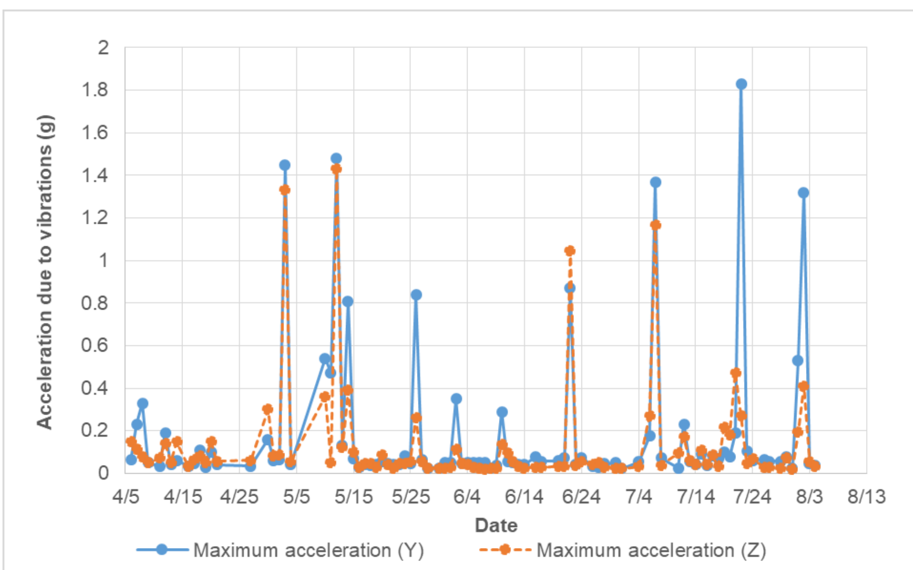

Figure 34. Maximum daily acceleration due to vibrations for the traffic signal

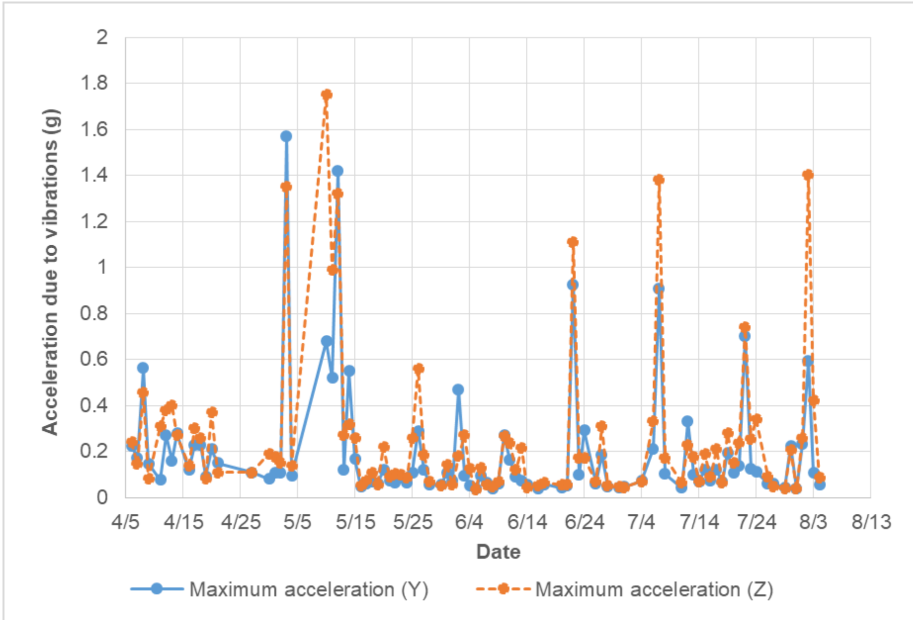

Figure 35. Maximum daily acceleration due to vibrations for the luminaire

Although the majority of wind was blowing along the Z direction, the acceleration data suggests that vibrations were still experienced in both the principal directions of the traffic signal and luminaire. This could be explained due to different wind phenomena like vortex shedding and galloping, which result in the movement of the structure perpendicular to the wind direction. This is opposite to the parallel movement as in the case of natural gusts. Previous research also showed that most of the higher modes (2nd or higher) in ancillary structures were due to vortex-shedding, which require low velocity, high-frequency steady wind speeds (10-35 mph) (Consolazio et al., 1998). According to FHWA, luminaires are susceptible to vortex shedding and natural gusts, whereas cantilevered signals are more susceptible to galloping and natural gusts (Garlich and Thorkildsen, 2005). Therefore, it is very likely that vortex shedding and galloping took place during the four months of field monitoring since the majority of observed wind speeds were low frequency and in the 15-35 mph range.

4.5.5 Anchor Rod Stress Data

The maximum daily bending stress values due to vibrations for both structures were converted into anchor rod axial stresses due to vibrations using bending moment and stress relationships (σ = My/I). Maximum daily rod stress values of the traffic signal due to vibrations from April to July are shown in Figure 36 and were found to be in the range of 0.5-4.5 ksi in either direction. The maximum value of rod stress due to vibrations observed in the traffic signal was 4.5 ksi in the Y direction and 3.9 ksi in the Z direction. The rod stresses in both principal directions of the traffic signal were similar to each other. However, the maximum daily axial rod stress due to vibrations recorded in the luminaire was more prevalent in the Z direction as compared to the Y direction (see Figure 37). The overall rod stress range was 0.25-3.5 ksi in both principal directions of the luminaire. The maximum value of axial rod stress due to vibrations observed in the luminaire was 3.3 ksi in the Y direction and 3.42 ksi in the Z direction. The stress data for both the structures was also suggestive of vibrations in both primary directions (Y and Z) throughout the four-month field monitoring period.

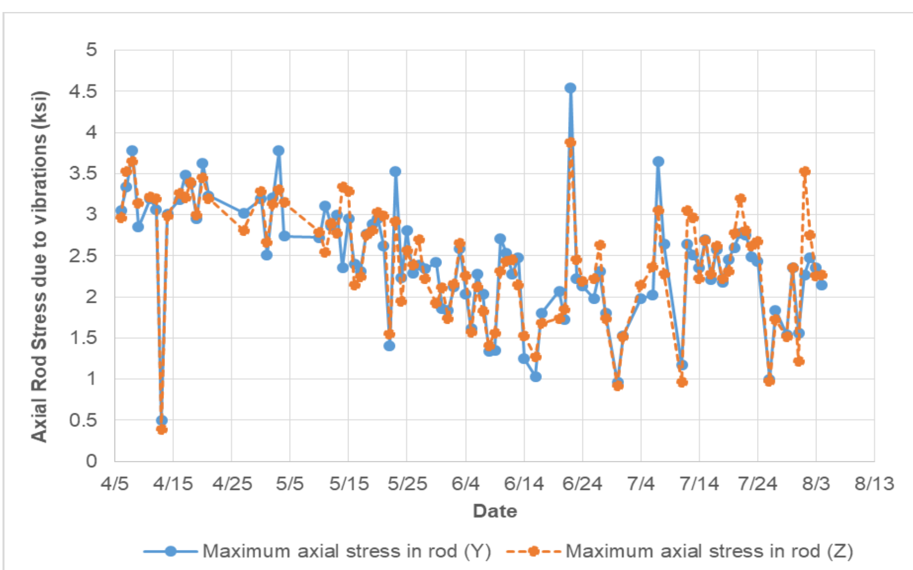

Figure 36. Maximum daily axial rod stress due to vibrations for the traffic signal

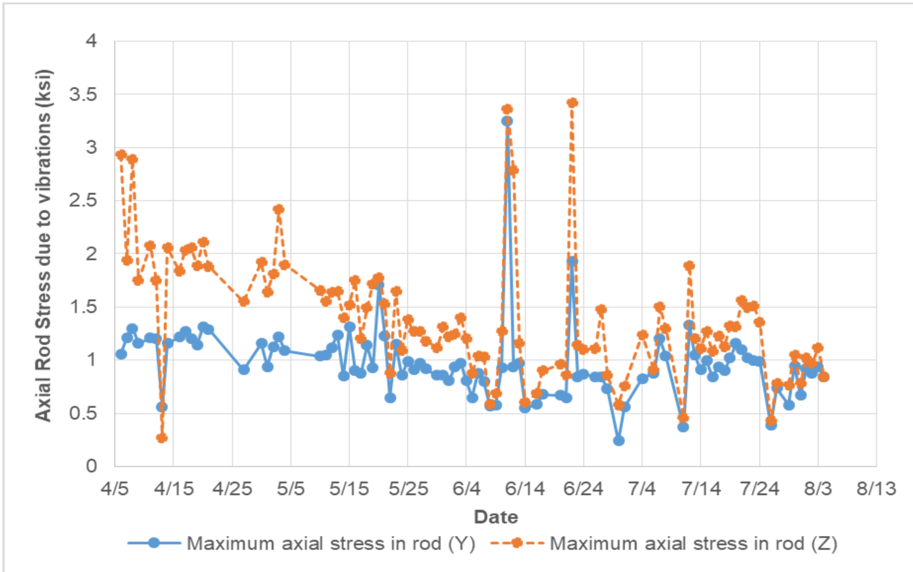

Figure 37. Maximum daily axial rod stress due to vibrations for the luminaire

4.5.6 Stress Histograms

A rainflow-count algorithm MATLAB 2018a was used to create stress histograms for the axial stress in the rods. This was performed to better understand the relationship between the stress range and the number of vibration cycles observed during the field monitoring. All the stress ranges with greater than 0.1% contribution from the number of vibration cycles were considered. For the traffic signal, the maximum significant stress range observed was 5 ksi with 0.15% contribution to the total number of vibration cycles. For the 5 ksi and 4 ksi stress ranges, approximately 22,000 and 420,000 cycles were observed in either direction for the traffic signal, respectively. The 1 ksi stress range had the maximum number of cycles (9.32 million) in the Z direction. The luminaire experienced 86,500 cycles at the maximum significant stress range of 3 ksi in the Z direction. The majority of vibration cycles experienced by the luminaire in the Z direction were in the 1 ksi stress range (11.60 million). Stress range histograms with a percentage contribution for both the traffic signal and the luminaire in the Z direction are shown in Figure 38 and Figure 39, respectively.

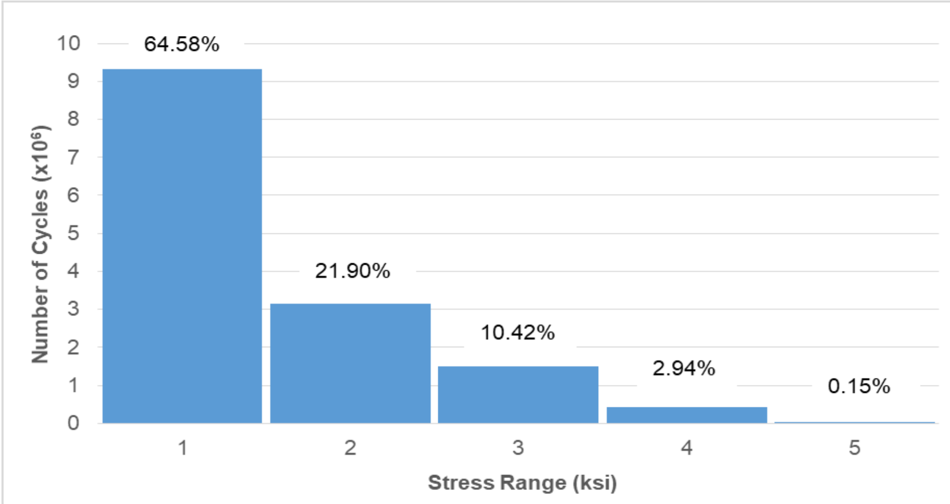

Figure 38. Rod axial stress range histogram for traffic signal in Z direction

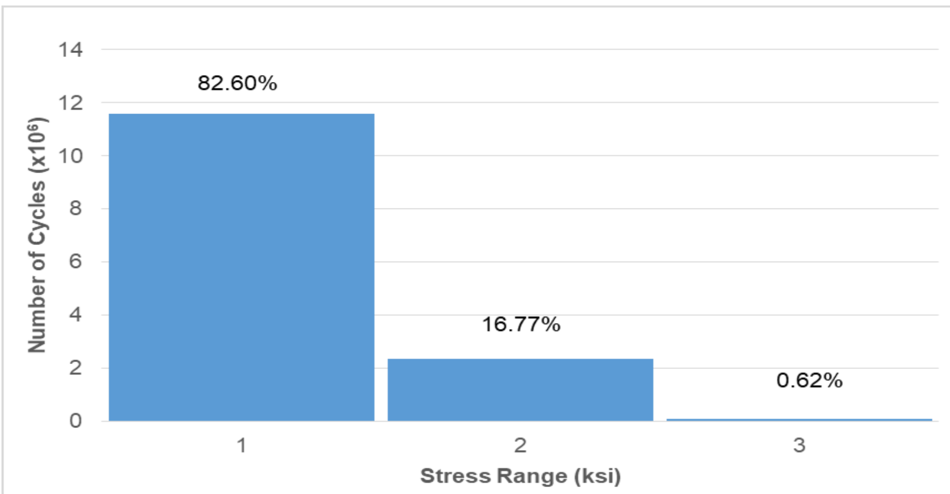

Figure 39. Rod axial stress range histogram for luminaire in Z direction

The stress range data was also extrapolated over a period of one year, and it was found that the traffic signal would experience approximately 4.51, 1.28, and 0.07 million cycles of 3 ksi, 4 ksi, and 5 ksi stress ranges, respectively. Similarly, the luminaire would experience 7.05 million and 0.26 million cycles of 2 ksi and 3 ksi annually.

In order to account for multiple stress ranges, an effective stress range was also determined for both the structures. The effective stress ranges were calculated using the cube root of the sum of the cubes of the measured stress ranges. The equation for the effective stress range as given in The Manual of Bridge Evaluation is shown in Equation 4 (AASHTO, 2011). The calculated effective stress range in the Z direction was approximately 2 ksi and 1.3 ksi for the traffic signal and luminaire, respectively. The effective stress range was small, but the vibration cycles are cumulative in nature. Therefore, it was decided to vibrate a full-scale traffic signal in resonance at the observed maximum stress range of 4-5 ksi obtained from the four-month field monitoring data.

$$\Delta f_{eff} = (\Sigma \gamma_i \Delta f_i^3)^{1/3}$$

Equation 4. Equation for effective stress range (AASHTO 2011)

4.5.7 Correlation between wind speeds, accelerations, and bending stresses

Daily maximum acceleration data with acceleration values > 0.1g were studied along with their corresponding daily maximum wind speeds to see if there was any correlation between them. It was found that wind speeds in the range of 20-40 mph produced acceleration values (>1g) on some days. However, on other days, similar wind speeds did not produce high accelerations (> 1g). This explains the variable frequency of high wind speeds. Also, on the day of highest wind speed event (46.9 mph), high accelerations of 1.75 g were observed in the luminaire but relatively smaller acceleration of 0.54 g in the traffic signal. It can be concluded that high winds do not necessarily produce high amplitude vibrations but depend on the frequency of the wind and resonant frequency of the structure.

Next, daily maximum bending stress data were studied along with their corresponding daily maximum wind speeds to see if there was any correlation between them. A similar pattern was observed as with the accelerations. The highest bending stresses were observed on the day with a wind speed of 39.2 mph. However, relatively smaller stresses were recorded on the day with the maximum wind speed of 46.2 mph. Therefore, it can be concluded that high wind speeds do not necessarily induce high stresses at the base of an ancillary structure.

4.6 Observations and Findings

1. The second and third modes of the traffic signal were the dominant modes with maximum contribution during the pluck tests and ambient wind-induced vibrations. These modes are the fundamental in-plane and out-of-plane modes of the long mast-arm attached to the straight pole. The first and second modes were found to have equal contribution in the case of the luminaire.
2. In spite of the majority of wind blowing from one direction, there was evidence of vibrations in both principal directions, which suggested occurrence of phenomenon like vortex shedding and galloping along with natural gusts.
3. The damping ratios for the luminaire were more than two times that of the traffic signal. Due to the long mast-arm of the traffic signal, the vibrations in the traffic signal took a longer time to damp out as compared to the luminaire.
4. The low stress ranges (≤ 5 ksi) contributed to the majority of the vibration cycles in both structures. The maximum significant stress range was found to be 5 ksi for the traffic signal and 3 ksi for the luminaire. After extrapolation of the data, it was concluded that the traffic signal would experience approximately 1.28 million cycles of 4 ksi stress range annually, and the luminaire would experience 0.26 million cycles of 3 ksi stress range annually.
5. Based on the results of the field monitoring, it was decided to vibrate a full-scale traffic signal in resonance at 4-5 ksi stress range during the large-scale experimental testing program.

CHAPTER 5: Vibration Testing of Ancillary Structures

Chapter 5 consists of an under-review manuscript titled "Investigation of Anchor Nut Loosening on Highway Ancillary Structures" submitted to the Journal of Structural Engineering on 03/05/2020. The manuscript presents the results and conclusions from the large-scale and small-scale vibration testing performed on anchor rods. The purpose of the testing was to investigate the effect of wind-induced vibrations on loosening of anchor nuts in ancillary structures.

Investigation of Anchor Nut Loosening on Highway Ancillary Structures

Japsimran Singh[1], Matthew H. Hebdon[2]

5.1 Abstract

Anchor nut loosening on highway ancillary structures has been a problem in the transportation industry for the past few decades. There have been reported cases in the past, where loose anchor nuts were found to be partially responsible for the failure of ancillary structures. Variable frequency winds can lead to resonant vibrations in ancillary structures, which are believed to be one of the potential causes of loose anchor nuts. Previous research also shows that transverse and axial vibrations can lead to loosening of nuts in structural and mechanical connections. This research was primarily focused on investigating the effect of wind-induced vibrations on loosening of anchor nuts in double-nut moment connections in ancillary structures. The research involved large-scale vibration testing of a four-anchor rod configuration traffic signal on the basis of vibration stress results from a four-month field monitoring program. The purpose of the large-scale

[1,2] Department of Civil & Environmental Engineering, 200 Patton Hall, Virginia Tech, Blacksburg, VA 24060

testing was to establish the relationship between the number of vibratory cycles, rod pretension, and nut loosening. A small-scale vibration test was also performed in a fatigue-rated universal testing machine to validate the results of the large-scale vibration testing.

5.2 Introduction

Many ancillary structures, such as cantilevered sign structures, overhead traffic signals, luminaires, and high-mast light towers (HMLT), have proved to be susceptible to wind-related fatigue and vibration issues (Dexter and Ricker 2002). Some of the more common problems in ancillary structures, resulting from wind-induced vibrations, include weld cracking at different locations, tube fracturing, loosening of anchor nuts, and cracking of anchor rods. Different wind loading phenomenon contribute to vibrations in the ancillary structures. Natural wind gusts can lead to vibration of the structure in the direction of wind whereas phenomenon like vortex shedding and galloping can result in vibration of the structure in a direction perpendicular to the wind direction.

There have been many reported cases in the past few decades where anchor nuts have been found loose on ancillary structures. Wind-induced vibrations are believed to be one of the potential causes of the observed anchor nut loosening. Previous research in other fields has also shown that transverse vibrations (perpendicular to the axis of the bolt or rod) can cause complete loosening of the nuts in structural and mechanical connections (Friede and Lange 2009; Jiang et al. 2003, 2004; Junker 1969; Yamamoto and Kasei 1984). On the other hand, there has been no evidence suggesting that axial vibrations (parallel to the axis of the bolt or rod) can result in total loss of pretension (Bickford 2008). However, early research showed that dynamic axial loading can lead to partial loosening of nuts (Goodier and Sweeney 1945). Axial vibration research also revealed that the rate of loosening is initially large during the first few thousand cycles but is dramatically reduced beyond that (Sauer et al. 1950). Sauer et al. also found that the rate of loosening is a function of the ratio of dynamic to static load (pretension) ratio and the amount of loosening decreases with an increase in bolt pretension (1950).

Nut loosening due to vibrations typically consist of two stages (Jiang et al. 2003). The first stage consists of negligible rotation of the nut accompanied by a small loss in pretension due to the local material deformation or plasticity at the thread roots. Once the pretension has reached a threhold value, it marks the beginning of the second stage, which involves rapid loss in pretension and fast backing off of the nut. The first and the second stages are also often refered to as non-rotational and rotational self-loosening stages, respectively (Mahmoud et al. 2016).

Double-nut moment connections, as shown in Figure 40, are primarily used for fastening ancillary structures to concrete foundations. Double-nut moment connections are currently required to be tightened as per the turn-of-the-nut tightening method (AASHTO 2015; Dexter and Ricker 2002; Garlich and Thorkildsen 2005). The tightening procedure involves snug-tightening the top nut and leveling nut followed by incremental angular tightening of the top nut based on the grade and diameter of the anchor rod. The tightening is followed by application of a verification torque equal to 110% of the final pretension to overcome any initial loosening due to stress relaxation within 48 hours of tightening (Dexter and Ricker 2002). Aside from a fully pretensioned top nut, there are no other means to prevent loosening of the nuts specified in the present tightening guidelines. The number of cases of anchor nut loosening is a matter of concern and poses a serious safety risk for the travelling public. Because the effect of wind-induced vibrations on anchor nut loosening is not well understood, and there is a safety risk associated with the anchor nut loosening, this topic needs further research.

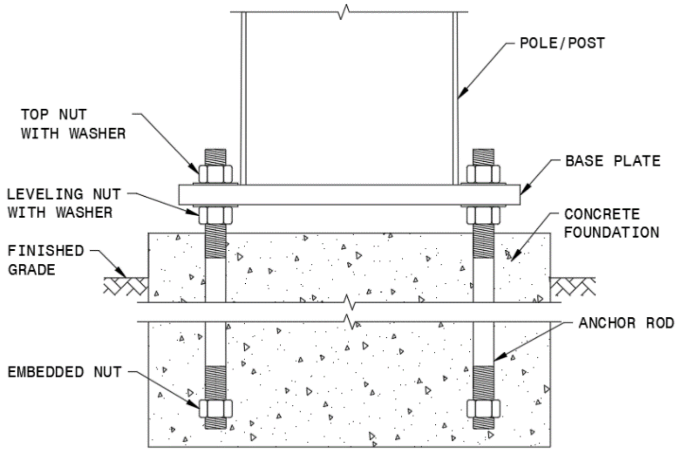

Figure 40. Typical double-nut moment connection on ancillary structures

5.3 Literature Review

Two cases of loose anchor nuts were reported during the failure incidents of two cantilevered sign structures in Michigan in 1990 (Till 1992). A combination of vortex shedding and loose anchor nuts were found to be the cause of failure. In 2012, two cantilevered sign structures collapsed onto a highway during heavy wind storms in Virginia, one each in Prince George County and Fairfax. Prior inspections of the structures revealed that these structures had loose anchor nuts. Loose anchor nuts were also found on HMLTs during 54 out of the 177 inspections done by the Alaska Department of Transportation (AkDOT) from 2007 to 2011 (Hoisington and Hamel 2014). Hoisington and Hamel also concluded that the nut loosening was not dependent on foundation type, pole height, lamp configuration, date of installation, number of anchor rods, rod diameter, or temperature during the time of installation.

Different private and government agencies have identified loose anchor nuts during field inspections across different states in the United States (Garlich and Koonce 2010). Loose anchor nuts are typically identified by striking washers and nuts in the field using a hammer. A “dull” sound as a result of the striking is an indication of a loose nut. However, this measure does not distinguish between a snug-tight or fully pretensioned connection (Garlich and Koonce 2010).

Loose anchor nuts can lead to higher stresses in the anchor rods and increase the flexibility of the base plate, contributing to the fatigue cracking in the welds and anchor rods (Garlich and Koonce 2010).

Most of the experimental or analytical research on ancillary structures in the past has been focused on issues like fatigue performance, anchor rod cracking, and weld cracking. The research on fatigue performance of tube-to-transverse plate fillet welds connecting the pole and the mast arm dates back to the 1970s (Alderson 1999; Archer and Gurney 1970; Miki et al. 1984; Miki and Masakaju 2001). In 1996, as part of an NCHRP 10-38 project, it was concluded from the static and fatigue tests conducted at Lehigh University that prying action due to the bearing of anchor nuts on the base plate can be eliminated by stiffening the plate (Dechant 1996). A base thickness equal to or greater than the anchor rod diameter can be used for this purpose. It was also found that the simple bending formula (My/I) and moment of inertia of the bolt group could be used to reasonably calculate the axial stresses in the anchor rods. Another large-scale fatigue testing program performed at the University of Texas at Austin was focused on enhanced fatigue performance of the connection between straight pole/mast arm and straight pole/foundation in traffic signal structures and high-mast lighting connections (Stam et al. 2011). One of the findings included the need to properly install anchor rods as loose anchor rods could cause stress concentrations near the weld toe and result in reduced fatigue performance.

Large-scale fatigue testing on ancillary structures in the past has been done using hydraulic actuators. Hydraulic actuators are easy to control and program but can sometimes take longer for testing due to low frequency rate. Resonance testing of ancillary structures is an alternative solution to actuator fatigue testing. Resonance testing involves vibrating the structure at its natural or resonant frequency using an external vibration source such as an electric motor. The forcing frequency of the motor is set equal to the natural frequency of the structure which leads to large amplitudes of vibration in the structure provided the structural damping is low. The amplitude of vibration can also be changed by slightly adjusting the forcing frequency around the natural frequency of the structure. In 1980, Van Dusen compared different methods for vibration testing of luminaires and concluded that resonance testing is one of the most affordable and time-saving methods for fatigue testing. Any significant change in stiffness can be easily detected by a change in frequency and a vibration exciter can also excite a luminaire in its fundamental mode (0.6-25 Hz) (Van Dusen 1980).

Hoisington and Hamel, whose research focused on the loosening of anchor nuts on ancillary structures evaluated finite element analysis (FEA) of anchor rods in three different connection models including a double nut moment connection (2014). The researchers analyzed the effect of loosening of nuts due to clamp load loss as a result of excessive permanent deformation in the connection. In their study, external loading in the form of moments simulating desing wind loads were applied on to the HMLP models to observe both clamp load loss and any separation between the connection elements. They discovered that double-nut moment connections required more than 100% design loads to cause any separation or clamp load loss. However, the authors recommended that thicker base plates and higher number of anchor rods should be used to increase the resistance of these connections to clamp load loss. Nassar and Matin also performed numerical analysis and experimental tests showing that cyclic separation forces can cause a loss of clamp load in a bolted joint if the bolt is tightened beyond the yield (Nassar and Matin 2006).

Recently, Iowa State University researchers in collaboration with the Minnesota Department of Transportation (MnDOT) also conducted two large-scale fatigue tests on a Type 5 signpost (Chen et al. 2018). The signpost consisted of twelve, 2.5 inch F1554 grade 55 anchor rods that were tightened to an average of 75% yield with a torque of 450 ft-lb using a modified open-ended torque wrench in a star pattern. Due to the stiffener plates at the base plate to pole connection, leveling nuts were fully pretensioned and top nuts were left snug-tight as opposed to conventional way of tightening which involves fully pretensioning the top nuts. Three out of the 12 anchor rods were also accidentally yielded during tightening. After tightening, the signpost was cycled at 1 Hz using a 55 kip hydraulic actuator at the free end of the pole. An effective stress range of 6 ksi was observed during an earlier field monitoring study and used as a target stress range for the fatigue test. After 2000 cycles of 6 ksi vibration stress loading, testing was stopped to check nut tightness. Upon inspection using striking of the washers and nuts with a hammer, one of the twelve anchor rod nuts was found to be partially loose. The nut tightness was also checked using the modified torque wrench. It was found that the inspected loose anchor nut began to turn at 180 ft-lb torque. A second large-scale fatigue test was also conducted at a lower stress range of 1 ksi. However, no loosening was observed after cycling the signpost for 1.24 million cycles.

Due to lack of sufficient past research in the field of anchor nut loosening in ancillary structures and historical evidence showing loose anchor nuts on ancillary structures throughout the United States, a research study consisting of an investigation into the effect of wind-induced vibrations on loosening of anchor nuts in ancillary structures was conducted. The research study involved a four-month field monitoring performed on a galvanized steel traffic signal and an aluminum luminaire to identify the magnitude and type of wind loads acting on these ancillary structures. A large-scale vibration testing was further conducted on a four-anchor rod traffic signal on the basis of vibration stress results from the field monitoring. The purpose of the large-scale vibration testing was to determine the relationship between vibration stress range, number of vibration cycles, anchor rod pretension, and loosening of anchor nuts. Lastly, a small-scale vibration testing consisting of axial vibrations in a single anchor rod fastened in a double-nut moment connection was conducted in order to validate the large-scale testing results.

5.4 Field Monitoring

Two previously installed ancillary structures (one aluminum luminaire and one galvanized steel traffic signal) close to each other were instrumented and monitored near the James River Bridge in Carrollton, Virginia for a four-month period from April 2018 to July 2018 (see Figure 41). The location was chosen on the basis of historical high wind speeds in the region due to the proximity to a large water body and minimal surrounding forest cover. The traffic signal consisted of eight, 2 inch diameter anchor rod fastened to a 21 feet high straight pole. The outside diameter of the straight pole of the traffic signal was 17 inch at the top and 19.5 inch at the bottom. The luminaire was a four 1 inch diameter anchor rod configuration structure with an overall height of 26 feet. The outside diameter of the straight pole of the luminaire was 6 inch at the top and 8 inch at the bottom. Multiple sensors, including accelerometers, wind anemometer, strain gages, and thermocouple, were instrumented on each structure. Pluck tests were conducted on the first day of the field monitoring program to identify and calculate the dynamic characteristics like modal frequencies and damping ratios of the individual structures. After the pluck tests, the ancillary structures were remotely monitored for wind-induced vibration data including accelerations, wind speeds, wind direction, vibration stress, and temperature change for a four-month period. However, only data pertaining to observed pole vibration stresses and anchor rod vibration stresses for the traffic signal is relevant to the discussion in this paper and hence, has been discussed in detail here.

Figure 41. Instrumented traffic signal and luminaire in Carrollton, VA

5.4.1 Instrumentation

A propeller-type anemometer (Model 05103: RM Young Company) was installed on top of the luminaire for recording wind speeds and wind direction. One tri-axial accelerometer (Model 3713E1125G: PCB Piezotronics, Inc.) was installed on top of each of the two structures for measuring the amplitude and frequency of accelerations due to wind loads. Eight temperature compensated strain gages (Model CEFLA: Tokyo Measuring Instruments Laboratory Co., Ltd.) were installed radially, 45˚ apart from one another on each pole above the hand-hole to record the bending stresses corresponding to the wind-induced vibrations, as shown in Figure 42. A Campbell Scientific CR5000 data logger was used for recording and monitoring data.

Figure 42. Wind monitor (left), Accelerometer (center), and Strain Gages (right)

The accelerometer and strain gage data was collected at a frequency of 50 Hz as compared to wind monitor data, which was collected at a lower frequency of 2 Hz. A higher frequency of 50 Hz ensured that all the structural frequencies less than or equal to the Nyquist frequency (25 Hz) were observed without any effect of aliasing. The accelerometer and strain gage data were also filtered through a sixth-order bandpass Butterworth filter with the cut-off frequencies set at 0.5 Hz (≤ half of the fundamental frequency of the poles in each direction) and 25 Hz (Nyquist frequency).

5.4.2 Results

In this paper, the direction parallel to the mast-arm plane for both poles has been denoted as Y, and the direction perpendicular to the mast-arm direction has been denoted as Z. During the four-month field monitoring period, a maximum wind speed of 47 mph and an average wind speed of 15 mph was observed. The majority of the wind was blowing from a direction perpendicular to the plane of the mast arm (Z) in both of the structures. However, stresses and accelerations were observed in both the principal directions (Y and Z) of the ancillary structures, which was likely due to the effects of wind phenomenon, like vortex shedding and galloping.

The measured pole bending stresses due to vibrations were used to calculate anchor rod axial stresses due to vibrations using simple bending moment and stress relationship ($\sigma = My/I$). The maximum daily anchor rod stress due to vibrations in the traffic signal was found to be 4.5ksi. The distribution of maximum daily rod stress due to vibrations for the traffic signal during the four-month field monitoring period is shown in Figure 43. A rainflow algorithm in Matlab (Model: R2019a) was further used to convert axial stress data in the anchor rods into vibration stress ranges. A histogram showing the relationship between the number of vibration cycles and the vibration stress range in the anchor rods along the Z direction of the traffic signal is plotted in Figure 44. Each histogram bin width was set as 1 ksi. For example, the stress ranges between 1 ksi and 2 ksi were summed under the 2 ksi histogram bin. The majority of cycles (9.32 million) for the traffic signal were due to 1 ksi stress range. Four ksi and 5 ksi stress ranges contributed approximately 420,000 and 22,000 cycles in either principal direction of the traffic signal during the four-month period. Stress ranges greater than 5 ksi had contribution less than 0.1% of the total vibration cycles and were considered negligible to the vibration accumulation.

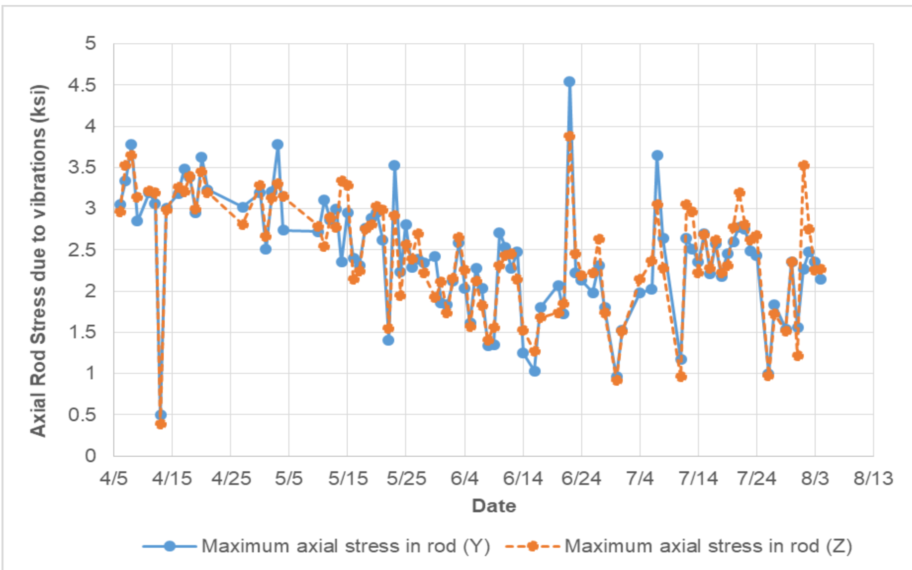

Figure 43. Maximum daily axial rod stress due to vibrations for the traffic signal

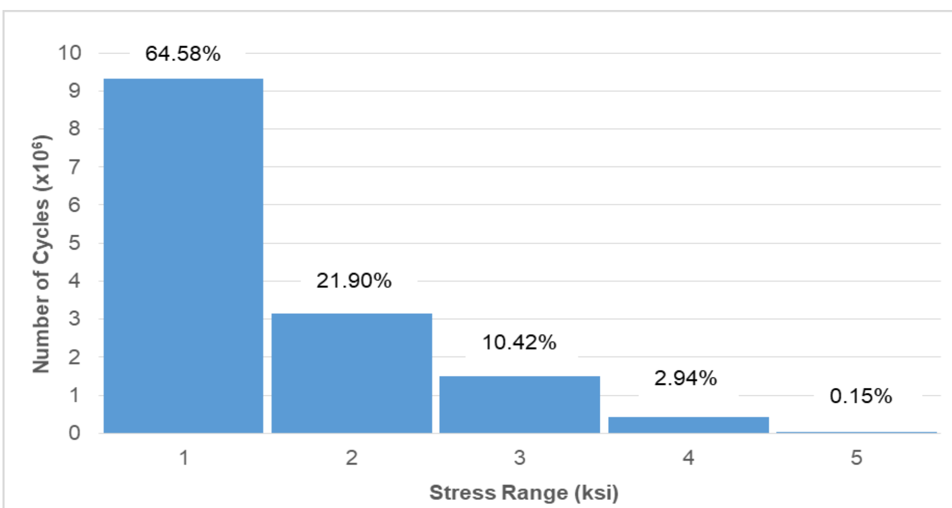

Figure 44. Vibration stress range histogram for anchor rods along Z direction

Based on an extrapolation of stress ranges over a period of one year, it was found that the traffic signal would have experienced approximately 4.51, 1.28, and 0.07 million cycles of 3 ksi, 4 ksi, and 5 ksi stress ranges, respectively. Based on the field monitoring vibration stress results, it was decided to vibrate a full-scale traffic signal in the laboratory at the highest observed stress range of 4-5 ksi. Due to the observance of multiple stress ranges throughout the field monitoring, an effective stress range was also calculated using the cube root of the sum of the cubes of the measured stress ranges, similar to that performed for fatigue evaluation of bridge structures. The equation as given in the AASHTO Manual for Bridge Evaluation is shown in Equation 5 (AASHTO 2011). The slope was chosen as 1/3 because of the lack of adequate data to support a different slope. The effective stress range was found to be 2 ksi for the traffic signal in the Z direction.

$$\Delta f_{eff} = (\Sigma \gamma_i \Delta f_i^3)^{1/3}$$

Equation 5. Equation for calculating effective stress range

5.5 Large-scale Vibration Testing

Wind-induced vibrations were simulated on a full-scale out-of-service, four-anchor-rod-configuration galvanized steel traffic signal. The pole wall was 0.1875 inch thick with an outer diameter of 11 inch at the bottom and 9 inch at the top. The traffic signal was 20 feet in height with a 1.5 inch thick galvanized base plate. The mast arm had a 0.1875 inch wall thickness with a 32 feet length. The anchor rods were F1554 grade 55 and 1.25 inch in diameter. The pole was vibrated in resonance using an eccentric weight motor attached at the free end of the pole. The eccentric weight and the frequency of the motor was varied for achieving desired vibrations. The anchor rods were instrumented with bolt strain gages to measure pretension. The effect of varying pretension and vibration stress range on nut loosening was investigated during individual vibration tests.

5.5.1 Experimental Test-setup

The anchor rods in a double-nut moment connection are generally embedded inside a concrete foundation. However, a reaction box fixture was used instead for simulating a fixed boundary condition during the testing. This ensured that multiple poles could be tested with the same reaction fixture. The lubricated anchor rods were first made snug-tight using a 22 inch long open-ended wrench and later fastened to 120˚ beyond snug-tight condition at the vertical plates of the reaction box fixture using a turn-of-the-nut tightening procedure (see Figure 45). The reaction box fixture was also stiffened using cross stiffeners. The traffic signal at the base plate was further fastened to the anchor rods in a double-nut moment connection (see Figure 45).

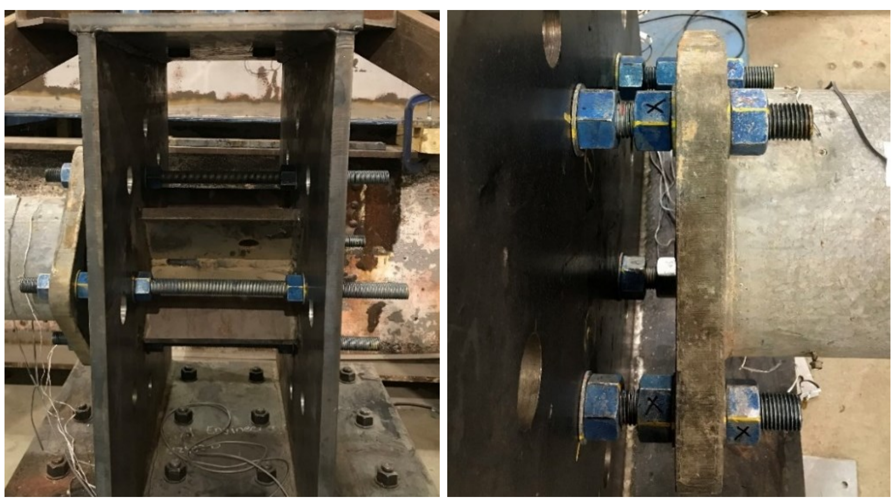

Figure 45. Reaction box fixture fastened to the anchor rods

The reaction box fixture was fastened to two W14x99 sections, which were connected at three locations to the floor of the laboratory, eight feet apart (see Figure 46). The two W sections were also connected using plates at the top and bottom to provide resistance to torsional movements during vibrations.

Figure 46. Complete view of the test-setup for large-scale testing

5.5.2 Instrumentation

A variable frequency industrial stepper motor (AMCI ISMD23E2-240E-M12) with a maximum torque capacity of 240 oz-in was used for inducing vibrations in the traffic signal (Figure 47). The motor was connected to a computer using an Ethernet cable and the motor frequency was input using a software interface. A weight was eccentrically attached to the motor shaft using a rotation arm. The eccentric weight produced a centripetal force large enough to induce vibrations in the pole at the free end.

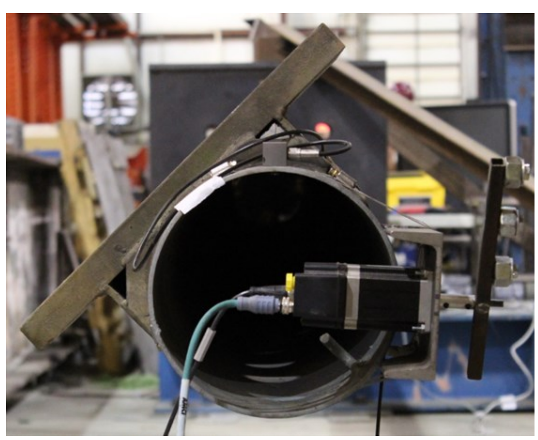

Figure 47. Variable frequency stepper motor attached to the free end of the pole

The bolt strain gages (Model BTM-6C-5LJBT: Tokyo Measuring Instruments Lab.) were placed 4.25 inch deep inside a 0.078 inch predrilled hole in the center of the anchor rods to measure anchor rod pretension. The bolt strain gage center was installed at the mid-depth of the double-nut moment connection to ensure proper measurement of pretension in the anchor rods. Foil strain gages (Model FLA-6-11-5LJCT: Tokyo Measuring Instruments Lab.) were also installed 2 feet above the hand hole to measure induced bending stresses in the pole during vibrations. One tri-axial MEMS DC accelerometer (Model 3713E1125G: PCB Piezotronics, Inc.) was attached at the free end of the pole to measure acceleration due to induced vibrations. A laser distance sensor (Model OPT 2011: Wenglor) was placed below the free end of the pole to measure free-end deflections. Tilt sensors (Model Tilt 33A: CTi) were attached to the flat surfaces of the anchor nuts to measure any nut rotations due to loosening during testing. All the sensors were connected to a CR5000 data acquisition system for recording and collecting data.

5.5.3 Experimental Test Procedure

Fifteen tests were conducted in total during the large-scale vibration testing. The first test involved vibration of the traffic signal with a 15-feet mast arm. The vibrations were induced in the 2^{nd} mode (fundamental out-of-the plane mode of the mast arm) of the traffic signal. After vibrating the pole for 600,000 cycles (including trial tests), a weld crack was observed on the connection between the mast arm and straight pole (see Figure 48). Due to weld cracking, the remainder of the fifteen tests were conducted on the straight pole in the first natural mode.

Figure 48. Weld crack at the connection between straight pole and mast arm

The following test procedure was adopted for the large-scale vibration testing:

1. The straight pole was fastened at the base plate to the lubricated anchor rods in a double-nut moment connection using a turn-of-the-nut procedure. It was ensured that there was a stand-off distance (less than one-bolt diameter) beyond the double-nut moment connection as per the VDOT tightening specification requirements (VDOT 2016a; b). Stand-off distance reduces the magnitude of any bending stresses in the anchor rods due to shear forces or torsional moments (Kaczinski et al. 1998). The anchor nuts were tightened with a 22 inch long open-ended wrench until the desired pretension in the anchor rods was achieved.
2. All of the sensors (pole strain gages, accelerometer, tilt sensors, and laser distance sensor) were installed, instrumented, and connected to the data acquisition system for recording data.
3. For the first test, the mast arm was connected to the straight pole using structural bolts, and the motor was attached to the free end of the mast arm for inducing vibrations. For all the other tests, the motor was mounted to the free end of the straight pole.
4. A pluck test was performed on the structure, which involved pulling the free end of the pole or the mast arm and releasing it to induce free vibrations. The free vibration data from

the different sensors was analyzed using Fast Fourier Transform (FFT) to determine the resonant frequencies.

5. The pole was vibrated in resonance by inputting the resonant frequency in the motor configuration settings.
6. Nut loosening was recorded throughout the testing using measured change in nut rotations and pretension.

5.5.4 Experimental Results

The testing configuration, modal frequencies, and vibration directions for all fifteen tests are shown in Table 14. Modal frequencies for the first natural mode were in the range of 4.6 Hz and 4.74 Hz. The difference in frequencies was due to the varying connection stiffness as a result of varying installation pretension in the anchor rods. The modal frequency for the first out-of-the plane mode of the mast arm was found to be 5.68 Hz. During the testing, a drop in modal frequency, stiffness, and vibration stress range was observed whenever the pole came out of resonance due to weld cracking or nut loosening. Therefore, in order to account for multiple stress ranges during testing, an effective stress range was calculated for individual tests (see Equation 5). The rod stress data was also converted into vibration stress ranges and corresponding vibration cycles using a rainflow algorithm in Matlab.

Table 14. Testing configuration, modal frequency, and vibration direction for large-scale tests

Test No.	Testing Configuration	Modal Frequency (Hz)	Mode	Vibration Direction
1	w/ mast arm	5.68	1st out-of-plane mode of mast arm	Perpendicular to the plane of the mast arm
2-15	straight pole	4.6 - 4.74	1st mode of straight pole	Vertical

Test 1

A summary of large-scale vibration testing results is shown in Table 15. The pole was vibrated with the mast arm in Test 1 at a vibration stress range of 1-3 ksi for 350,000 cycles. The average pretension in the anchor rods at installation was approximately 30 ksi, which is 66% of the minimum installation pretension of 45 ksi for grade 55 anchor rods. A total drop of 4% in pretension was observed with the majority of loss in the initial few hours of testing. The maximum change in nut rotation of 1˚ was observed for one of the four anchor rods throughout the test. After 350,000 vibration cycles, a weld crack was observed at the mast arm to the pole connection.

Table 15. Summary of large-scale vibration testing

<table>
<tr><th>Test Number</th><th>Configuration</th><th>Effective Stress Range (ksi)</th><th>Number of Cycles (millions)</th><th>Average Initial Pretension in Rod (ksi)</th><th>Maximum Percentage Loss in Pretension Observed in any Rod (%)</th><th>Maximum Change in Nut Rotations Observed in any Rod (˚)</th></tr>
<tr><td>1</td><td>w/ mast arm</td><td>1-3</td><td>0.35</td><td>29</td><td>4</td><td>1</td></tr>
<tr><td colspan="7">Weld fatigue crack at mast arm to pole connection</td></tr>
<tr><td>2</td><td rowspan="2">w/o mast arm</td><td>2</td><td>1.01</td><td>32.5</td><td>3.63</td><td>1.8</td></tr>
<tr><td>3</td><td>2-4</td><td>0.34</td><td>33</td><td>4.16</td><td>< 1</td></tr>
<tr><td colspan="7">Weld fatigue crack at base plate to pole connection. Pole replaced.</td></tr>
<tr><td>4</td><td rowspan="2">w/o mast arm</td><td>5.5</td><td>1.01</td><td>12.75</td><td>20</td><td>1.1</td></tr>
<tr><td>5</td><td>6</td><td>1.57</td><td>11.22</td><td>25.8</td><td>1</td></tr>
<tr><td colspan="7">Weld fatigue crack at base plate to pole connection. Pole replaced.</td></tr>
<tr><td>6</td><td rowspan="10">w/o mast arm</td><td>5.5</td><td>10.15</td><td>8.14</td><td>NA</td><td>1.5</td></tr>
<tr><td>7</td><td>6</td><td>4.8×10^{-4}</td><td>Hand-tight</td><td>100</td><td>Loose</td></tr>
<tr><td>8</td><td>4</td><td>2.25</td><td>3</td><td>100</td><td>4.5</td></tr>
<tr><td>9</td><td>3</td><td>2.23</td><td>2</td><td>100</td><td>2</td></tr>
<tr><td>10</td><td>3.4</td><td>1.31</td><td>4</td><td>100</td><td>3.3</td></tr>
<tr><td>11</td><td>5.2</td><td>5.06</td><td>5.5</td><td>52.4</td><td>0.14</td></tr>
<tr><td>12</td><td>4.4</td><td>2.67</td><td>2</td><td>73.5</td><td>1.42</td></tr>
<tr><td>13</td><td>4.8</td><td>3.46</td><td>3</td><td>68.2</td><td>4.8</td></tr>
<tr><td>14</td><td>4.8</td><td>3.5</td><td>4</td><td>81</td><td>3.28</td></tr>
<tr><td>15</td><td>5.1</td><td>20.23</td><td>5</td><td>56.4</td><td>NA</td></tr>
</table>

Tests 2-6

All of the tests after Test 1 were conducted on the straight pole in the fundamental mode in the vertical direction. The stress range and pretension parameters for Test 2 and Test 3 were similar to Test 1. However, the pole was vibrated for a longer time (1 million cycles) in Test 2. The percentage loss in pretension and nut rotations were also similar to Test 1. At the end of Test 3, a weld crack was observed at the base plate to pole connection and the pole was replaced (see Table 15).

The vibration stress range in tests 4 and 5 were increased to 5.5 ksi and 6 ksi, respectively, close to the target vibration stress range from the field monitoring results. The initial pretension was also subsequently decreased to approximately 13 ksi in both tests (see Table 15). The poles were cycled for more than 1 million cycles but negligible nut loosening (1˚) was observed during both tests. The top anchor rod in tests 4 and 5, which was oriented to achieve the largest stress, experienced a pretension drop of 20% and 26%, respectively (see Table 15). The majority of this loss was during the first few thousand cycles, as shown in the pretension loss curve for Test 4 in Figure 49. This initial drop was believed to be due to local material deformation at the threads, stress relaxation, and differential thermal expansion and was accelerated due to vibrations. After Test 5, the pole was again replaced due to the development of a weld crack at the base plate to pole connection.

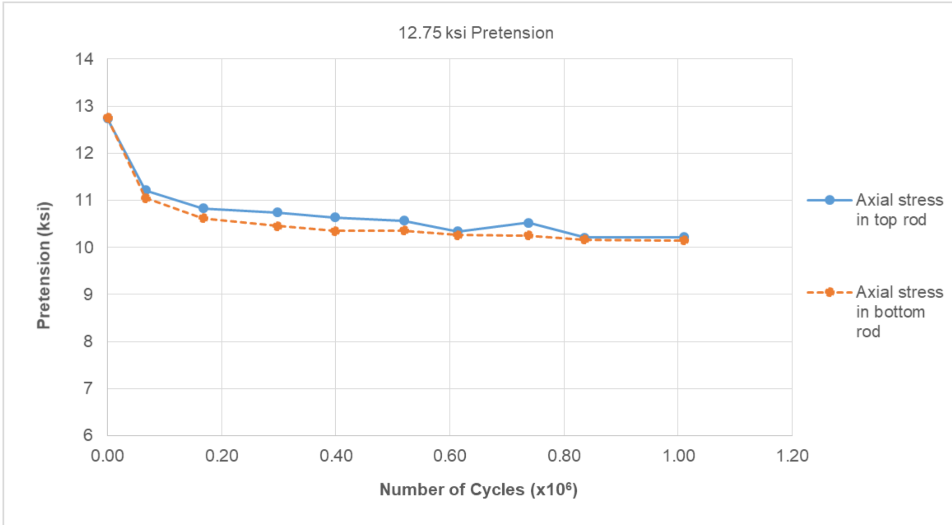

Figure 49. Pretension loss curve for Test 4

A small nut rotation (< 2˚) was observed during Test 6 when the pole was vibrated at 5.5 ksi stress range for 10 million cycles with an initial pretension of 8 ksi (see Table 15). During Test 6, significant changes in ambient temperature around the test setup induced thermal stress fluctuations in the bolt strain gages. Bolt strain gages were not temperature compensated, and no dummy gage was instrumented until Test 6 to account for any thermal stresses. Therefore, pretension drop, if there was any, was not recorded during Test 6. Subsequent vibration tests involved the use of dummy bolt stain gage for data analysis.

Tests 7-11

After the first six tests experienced negligible nut rotations, the initial pretension on subsequent tests was decreased to less than 5 ksi to determine whether loosening takes place at lower pretension levels. Test 7 involved vibration testing of the pole with only hand-tightened anchor nuts. A complete loss of pretension along with backing off of the nuts was observed after only 480 cycles of 6 ksi vibration stress range (see Table 15). Following this, the anchor rod pretension in tests 8, 9, and 10 was set at 3, 2, and 4 ksi, respectively. The vibration stress range was initially set close to 5 ksi, but due to progressive loosening of the nuts and drop in stiffness during testing, the effective stress range for all the three tests was in the range of 3 to 4 ksi. A slow but steady drop in pretension in the top anchor rod in approximately 2 million cycles was observed in all three tests. The pretension loss curve for Test 8, with 3 ksi initial pretension, is shown in Figure 50. An overall nut rotation of 4.5˚ in the top nut was observed during Test 8.

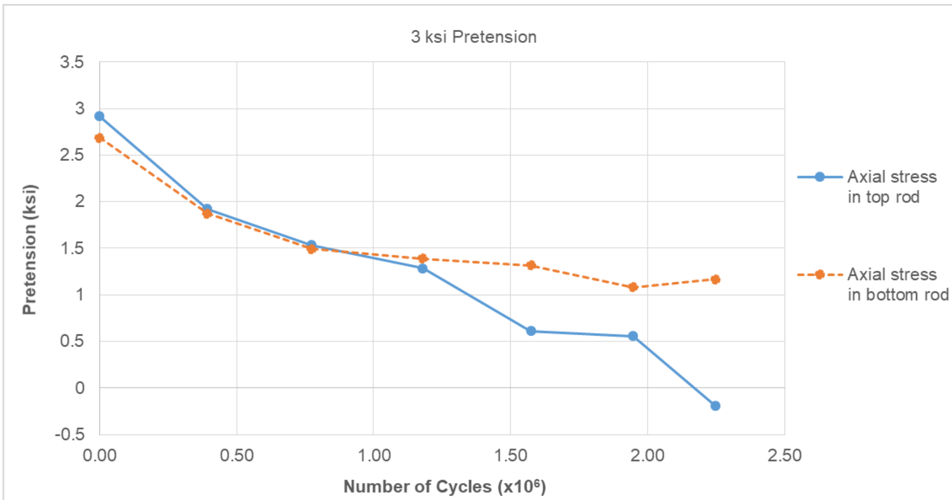

Figure 50. Pretension loss curve for Test 8

After complete pretension loss in tests 8, 9, and 10, anchor rod pretension was set at 5 ksi in Test 11. The test was stopped after 5 million cycles of 5.2 ksi stress range. A pretension loss of 52% with negligible nut rotations (<1˚) was observed during Test 11 (see Table 15). The pretension loss curve for Test 11 is shown in Figure 51. Similar to tests 1-6, the majority of initial loss in pretension in Test 11 was believed to be due to stress relaxation and local deformation at the threads. From the above results of tests 7-11, it can also be concluded that the anchor nut loosening due to 4-5 ksi vibration stress range begins to happen at lower levels of pretension (< 5 ksi). Therefore, improper tightening (tightening at lower levels of pretension i.e. < 5ksi) along with wind-induced vibrations can lead to anchor nut loosening.

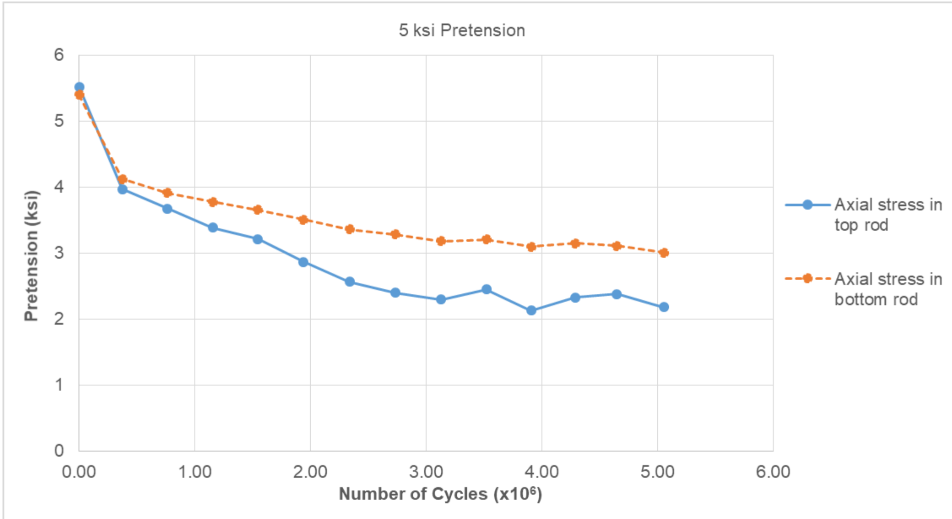

Figure 51. Pretension loss curve for Test 11

Test 12-15

Repetition of vibration testing at 2, 3, and 4 ksi initial pretension was performed in tests 12, 13, and 14, respectively, to determine the variation in loosening behavior at each of the pretension levels. The effective stress range was in the range of 4 to 5 ksi for the tests. The anchor rods did not become completely loose in any of the three tests; however, pretension loss was high (70% to 80%) after 2.5-3.5 million vibration cycles. The pretension loss curve for Test 13, involving repetition test for 3 ksi pretension, is shown in Figure 52. The pole in Test 13 was going in and out of resonance after 3.5 million cycles; therefore, the test was stopped with approximately 68% loss in pretension. The anchor nuts were almost completely loose after vibration testing in tests 12, 13, and 14 and were backed off using minimal wrench torque. The nut loosening curve for the top and bottom anchor rods in Test 13 is shown in Figure 53.

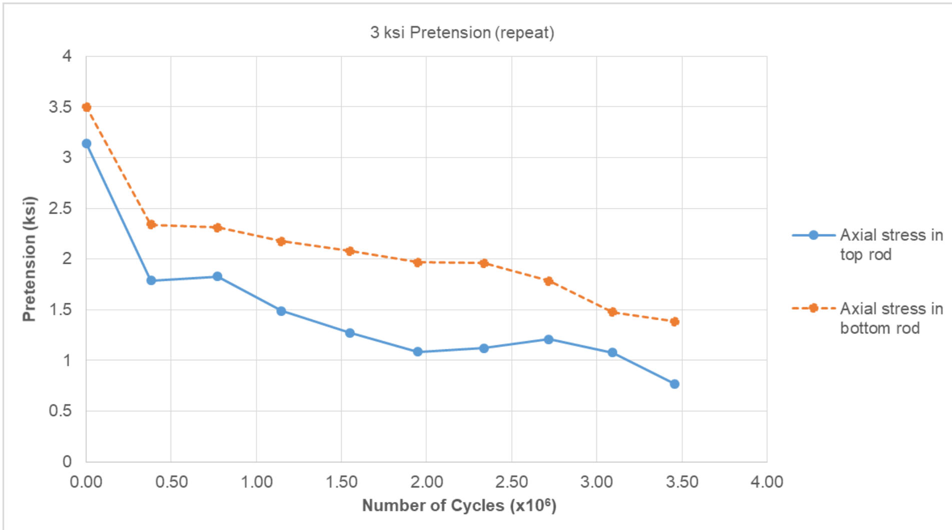

Figure 52. Pretension loss curve for Test 13

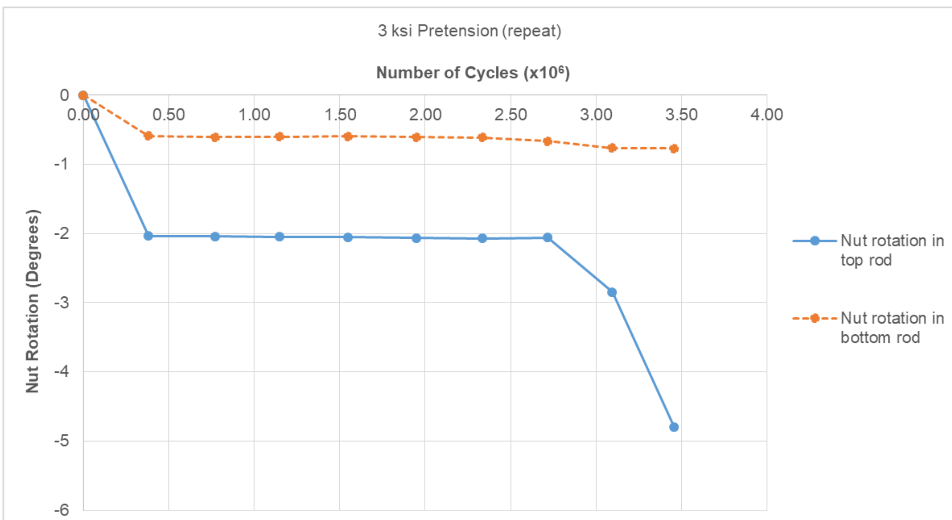

Figure 53. Nut loosening curve for Test 13

After Test 14, it was decided to perform vibrations at 5 ksi initial pretension for a longer period of time in Test 15. The anchor rods did not become completely loose and experienced a 56% drop in pretension after 20 million cycles of 5 ksi vibration stress range indicating that anchor rod loosening begins to happen below the threshold of 5 ksi initial pretension. The nut rotations were not reported for Test 15 since the tilt sensors used for measurement of nut rotations did not function properly during the vibration testing.

Loosening behavior

When an anchor nut becomes totally loose, the overall behavior of pretension and nut rotation in the anchor rods during vibration loosening, as indicated in the above results, can be divided into three stages. The first stage involves relatively small nut rotations accompanied by a quick loss in pretension due to accelerated relaxation and local material deformation at the threads. The second stage consists of plateauing or steady loss of the pretension and nut rotation over time. The third stage involves the sudden backing of the nut leading to complete loss in pretension, a behavior like this is evident from the loosening curves shown in Figure 52 and Figure 53.

5.6 Small-scale Vibration Testing

Vibration testing of a single anchor rod in a double-nut moment connection was performed in a 110 kip fatigue-rated MTS universal testing machine (UTM). The anchor rod connection was vibrated in an axial direction (parallel to the direction of the axis of the rod) on the basis of the results from large-scale testing. The objective of the testing was to validate and verify the large-scale vibration testing results. The vibration frequency and amplitude rate were adjusted to match the results from the field monitoring and large-scale vibration testing. ASTM F1554 grade 55-1 inch diameter anchor rods were used for the vibration testing. The test rod was instrumented with bolt strain gage for pretension measurement during testing. The effect of varying pretension and vibration stress range were investigated through different individual tests similar to the large-scale vibration testing.

5.6.1 Experimental Test-setup

The test anchor rod was passed through a hole in the center of a 1 inch thick ASTM A36 steel base plate with dimensions 24 inch x 12 inch. The test anchor rod was fastened in a double-nut moment connection at the base plate. The top end of the test anchor rod was fastened to a top built-up fixture. The base plate was fastened to a bottom built-up fixture using two, 1.5 inch diameter threaded rods. The top and the bottom built-up fixture were clamped in the grips of the fatigue testing UTM. The test anchor rod in the double-nut moment connection was axially vibrated using sinusoidal cyclic forces. The loading frequency was set close to the first mode frequency (4.7 Hz) of the pole, as observed during the large-scale vibration testing. The base plate was also braced to prevent any lateral movement during testing. A schematic and photograph of the test-setup is shown in Figure 54.

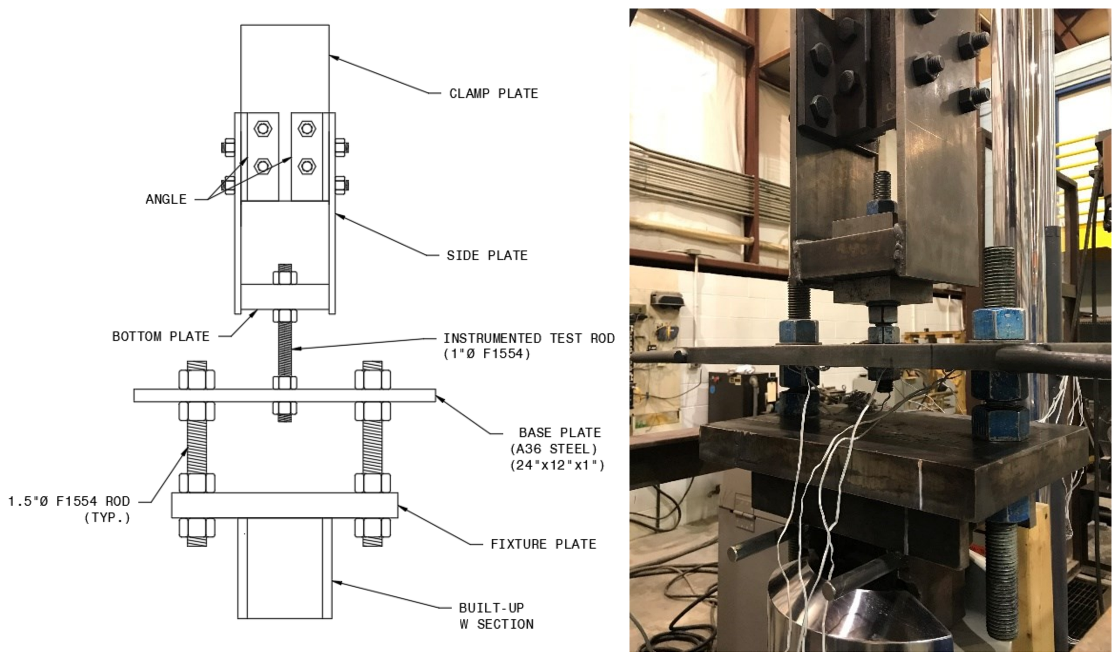

Figure 54. Small-scale vibration test-setup–Schematic (left) and Photo (right)

5.6.2 Instrumentation

A bolt strain gage (Model BTM-6C-5LJBT: Tokyo Measuring Instruments Lab.) was installed 2 inch deep inside a 0.078 inch predrilled hole in the center of the test anchor rod. The center of the gage was at the mid-thickness of the base plate for measurement of maximum tensile stress in the anchor rod. The anchor nut surfaces and base plate were marked with a black marker to visually check for any loosening of the nut during testing. A dummy gage was also installed in an anchor rod similar to the test rod to account for any thermal stress variations during the vibration testing. Bolt strain gages were connected to a CR5000 data acquisition system for data recording and collection.

5.6.3 Experimental Test Procedure

Six axial vibration tests were performed in total. Each vibration test involved the following test procedure:

1. The threads and bearing surfaces of the anchor rod and anchor nuts were lubricated with beeswax. The anchor rod was fastened to the base plate in a double-nut moment connection using a turn-of-the-nut procedure. The anchor nuts were tightened using a 15-inch long adjustable wrench until the desired pretension level, as measured by the bolt strain gages, was achieved.
2. The anchor nuts and the base plate were marked with a black marker to check for any change in nut rotations.
3. The frequency and force amplitude rate of the fatigue testing machine were increased until the required vibration speed and stress range were achieved, respectively.
4. Any loss in pretension or change in nut rotation was recorded periodically.

5.6.4. Experimental Results

A summary of the small-scale vibration tests, including vibration frequency, effective stress range, number of cycles, initial rod pretension, and percentage loss in pretension, is shown in Table 16. The anchor rod was vibrated at a loading frequency of 4 Hz for the first five tests, and at 4.7 Hz for the sixth test. The testing was done at critical levels of pretension (≤ 34 MPa (5 ksi)) identified from the large-scale testing results. Vibration tests 1 and 2 were performed at an initial pretension of 3 ksi and 2 ksi, respectively. Anchor rods in both the tests experienced a pretension loss of 87% each after approximately 2 million cycles when cycled at an effective stress range of 3.43 ksi (see Table 16). The vibration loosening curve for Test 2 is shown in Figure 55.

Table 16. Summary of small-scale vibration results

Test Number	Vibration Frequency (Hz)	Effective Stress Range (ksi)	Number of Cycles (millions)	Initial Pretension in Rod (ksi)	Percentage loss in Pretension (%)
1	4	3.43	1.81	3	87.6
2		3.43	2.04	2	87.1
3		3.79	4.93	4	51
4		4.28	3.7	2	73.4
5		4.63	2.66	3	55.9
6	4.7	5	20.1	5	61.1

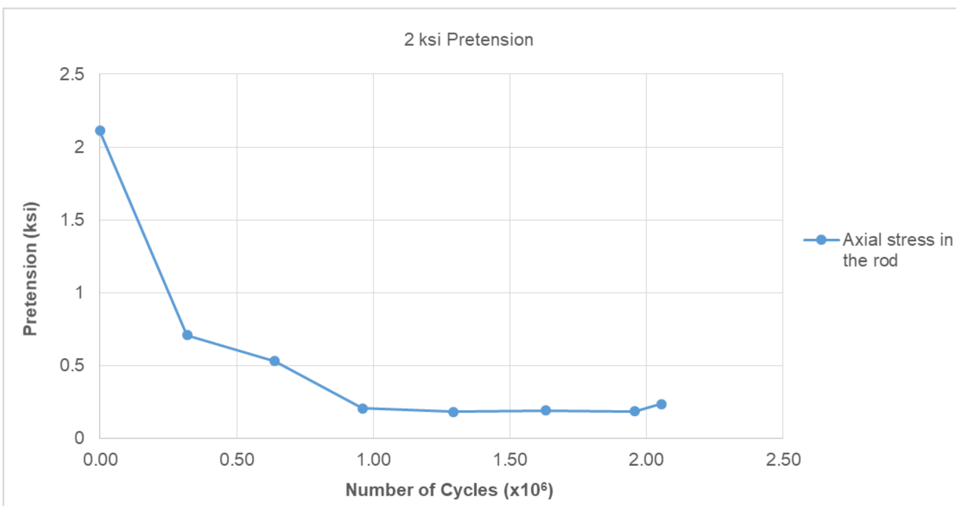

Figure 55. Vibration loosening curve for Test 2

Test 3 involved vibration testing at 4 ksi rod pretension. The anchor rod experienced a 51% loss in pretension after 5 million cycles of 3.8 ksi vibration stress range (see Table 16). The majority of the pretension loss was in the first few thousand vibration cycles as shown in Figure 56. Tests 4 and 5 were repetition tests for 2 ksi and 3 ksi pretension levels, respectively. The loosening behavior of the anchor rods in tests 4 and 5 was similar to the loosening behavior in tests

1 and 2, respectively. However, the anchor rods in tests 4 and 5 did not become completely loose after 3.7 million and 2.7 million cycles, respectively. There was still approximately 0.6 ksi and 1.5 ksi pretension left in the anchor rod for tests 4 and 5, respectively. Test 6 involved vibration testing at the pretension threshold of 5 ksi identified from the large-scale testing. The anchor rod experienced a 61% pretension loss after 20 million cycles of 5 ksi vibration stress range.

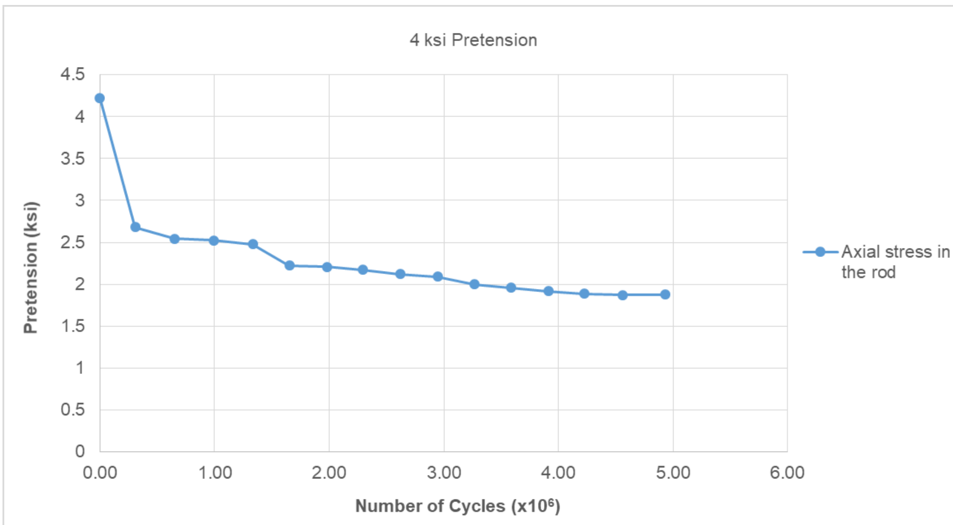

Figure 56. Vibration loosening curve for Test 3

Comparison of large-scale and small-scale vibration testing

The pretension threshold below which the anchor nut loosening starts was 4 ksi in the small-scale vibration testing as compared to 5 ksi in the large-scale vibration testing (see Figure 51 and Figure 56). The difference in pretension threshold was believed to be due to the secondary contribution of other types of vibrations, like transverse and rotational vibrations during the large-scale vibration testing. However, the overall pretension loosening behavior along with number of vibration cycles for the anchor rods was found to be similar in both large-scale and small-scale vibration tests (see Table 15 and Table 16). A comparison of the pretension loosening curves at 3 ksi pretension performed for both the tests is shown in Figure 57. The overall behavior, or the general shape of loosening, was same for all the tests; however, the large-scale vibration tests involved a gradual decrease in pretension over time as compared to the small-scale vibration tests (see Figure 57).

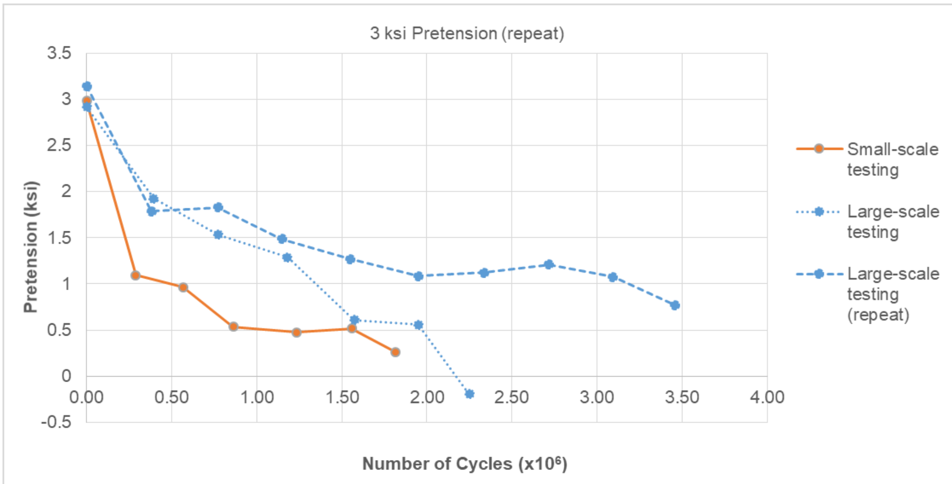

Figure 57. Comparison of pretension loosening curves at 3 ksi initial pretension

A combined pretension loosening graph of all the tests performed during the large-scale and small-scale testing is shown in Figure 58. The graph provides a good representation of the pretension threshold (5 ksi) below which nut loosening occurred during the individual tests. The pretension loss was not recorded during Test 6 of the large-scale testing due to thermal stress fluctuations and an expected pretension loosening curve has been shown with the dotted lines in Figure 58. The expected loosening behavior for anchor rod in Test 6 is similar to the other tests with pretension higher than 5 ksi and small nut rotations.

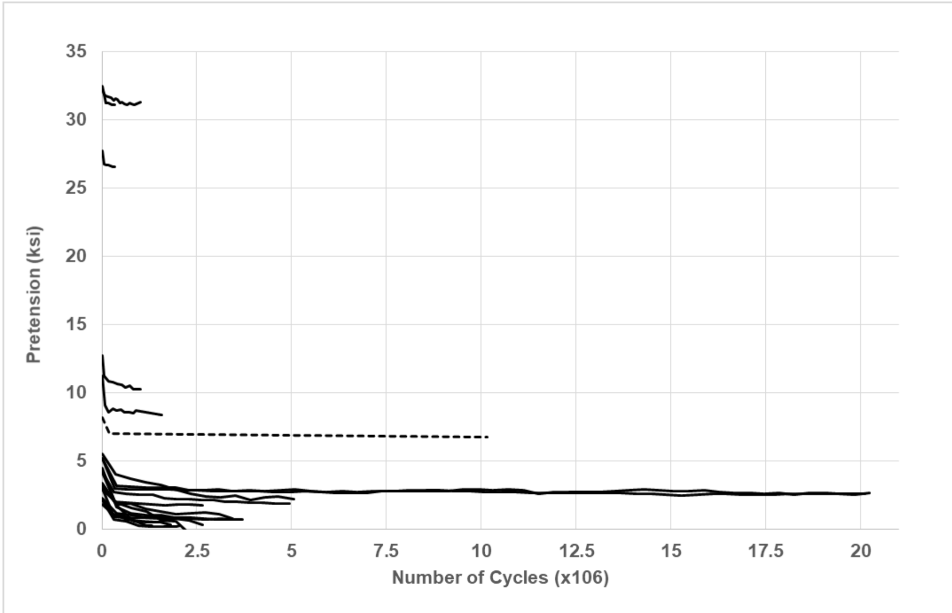

Figure 58. Initial pretension vs number of vibration cycles for all vibration tests

5.7 Conclusions

Based on the four month field monitoring program, large-scale vibration testing, and small-scale vibration testing performed on ancillary structures, the following conclusions can be made regarding the loosening of anchor nuts on ancillary structures:

1. The majority of wind-induced vibration cycles on the instrumented traffic signal were due to low vibration stress ranges (≤5 ksi) with maximum contribution of 9.32 million cycles from 1 ksi stress range. Four ksi and 5 ksi vibration stress ranges contributed 420,000 and 22,000 cycles during the four month field monitoring period. After extrapolation of the anchor rod vibration stress range data, it was concluded that the traffic signal should experience approximately 4.51, 1.28, and 0.07 million cycles of 3, 4, and 5 ksi vibration stress ranges in either of the principal directions during one full year. Therefore, the target vibration stress range was set in the range of 4 to 5 ksi for large-scale vibration testing.
2. Vibration stress and acceleration data suggested vibrations in both of the principal directions of the instrumented traffic signal and luminaire in spite of the majority of the

wind blowing from one direction during the field monitoring. This occurrence are likely due to wind phenomenon like vortex shedding, and galloping, along with natural gusts.

3. It was concluded from the large-scale testing that improper tightening (tightening at low levels of pretension) of anchor rods in ancillary structures can lead to loosening of the anchor nuts when subjected to wind-induced vibrations. It was observed that loosening of anchor nuts on the tested traffic signal occurred at pretension levels less than 5 ksi. The anchor rods with initial pretension greater than or equal to 5 ksi did not become completely loose when cycled for approximately 20 million cycles at 4 to 5 ksi vibration stress range. Anchor rods with initial pretension of 2, 3, and 4 ksi became completely loose within 1.5-3.5 million cycles.
4. The initial pretension threshold for loosening was found to be approximately 4 ksi during small-scale testing and 5 ksi during large-scale testing. The observed loosening during the small-scale testing occurred more rapidly compared to the large-scale testing; however, the total number of vibration cycles to loosening along with overall loosening behavior was found to be similar in both large-scale and small-scale vibration testing. The small-scale vibration testing provided validation for the large-scale testing conducted on a full-scale traffic signal.
5. The overall behavior of anchor nut loosening observed during both the vibration tests can be described by three stages. The first stage consists of a fast drop in pretension and relatively small nut rotation due to accelerated initial relaxation and local deformation at the threads. The second stage involves a slow and steady loss of pretension and change in nut rotation. The third stage involves a sudden rapid nut rotation leading to a complete loss in pretension.

CHAPTER 6: Thread Fabrication Tolerance and Snug-tight Study

Chapter 6 consists of an under-review manuscript titled "Effect of Thread Fabrication Tolerance and Snug-tight on the Loosening of Anchor Nuts in Highway Ancillary Structures" submitted to the ASCE International Conference on Transportation and Development 2020 on 12/16/2019. The manuscript compares results from a thread tolerance study conducted on anchor rods and nuts procured from 3 suppliers in Virginia with the allowable tolerances specified in ASTM. The results from the variation in snug-tight pretension due to wrench length and personnel strength have also been discussed in detail in the manuscript.

Effect of Thread Fabrication Tolerance and Snug-tight on the Loosening of Anchor Nuts

Japsimran Singh, [1] and Matthew H. Hebdon, Ph.D., PE, [2]

6.1 Abstract

Loose anchor nuts on ancillary structures in the transportation industry pose a serious safety risk to the traveling public. The exact cause of anchor nut loosening is unknown, but thread tolerances and improper tightening are believed to be some of the potential causes. ASTM F1554 and A563 specify allowable tolerances for galvanization and overtapping on anchor rods and nuts, respectively. Too tight of a tolerance fit would not allow for free turning of the nut onto a rod, whereas a loose tolerance fit could lead to loosening of the nuts upon vibration and reduced pretension. Additionally, the snug-tight condition is vaguely defined in the tightening specifications, with variations leading to under-tightening or over-tightening during the turn-of-the-nut tightening procedure. The thread parameters of anchor rods and nuts procured from three

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[1,2] Department of Civil & Environmental Engineering, 200 Patton Hall, Virginia Tech, Blacksburg, VA 24060

suppliers were investigated using Digital Image Analysis. The thread parameters were found to be within allowable tolerances indicating that nut loosening is unlikely to occur due to thread tolerance related issues. The investigation of snug-tight pretension in a double-nut moment connection revealed that snug-tight stress is highly variable due to the variable wrench length and personnel strength, and can lead to under-tightening or over-tightening of the connection during the turn-of-the nut tightening procedure.

6.2 Background

Anchor rods and nuts are commonly used to fasten ancillary traffic structures to a foundation. Ancillary traffic structures typically include overhead sign structures, traffic signals, luminaires, and high-mast light towers. Double-nut moment connections are commonly used for overhead sign structures, traffic signals, and high-mast light towers, whereas luminaires primarily consist of single-nut connections. Over the past few decades, there have been some failure incidents where ancillary structures have collapsed onto roadways. During the subsequent inspections, loose anchor nuts were found to be partially responsible for the failures. Loose anchor nuts lead to higher stresses in the anchor rod and further contribute to the potential collapse of the ancillary structures. The exact cause of loose anchor nuts is unknown, but potential causes include thread tolerances, improper tightening, and wind-induced vibrations. This research study evaluates the effect of the first two potential causes–thread tolerances and improper tightening due to variable snug-tight pretension.

Anchor rods and nuts are galvanized to prevent their corrosion in the field during their service life. ASTM F1554 and A563 specify allowable zinc build-up and overtapping allowances on the external and internal threads of the anchor rod and anchor nut, respectively, as shown in Table 17 and Table 18 (ASTM 2015a; b). The anchor nuts are tapped oversized after a hot-dip galvanization process to minimize the likelihood of rejection due to the inability to run the nut up the threads by hand. Poor quality control during manufacturing can lead to improper galvanization and excessive overtapping, further facilitating the creation of larger gaps between the mating threads of the anchor rod and nut. A loose tolerance fit due to larger gaps can potentially lead to loosening of the nuts upon vibration and even reduced pretension after tightening.

Table 17. Allowable Zinc Buildup on ASTM F1554 Anchor Rods (ASTM 2015a)

Nominal Diameter (in.)	Threads/ in.	Diametrical Zinc Buildup, in.	Maximum Anchor Rod Diameter (in.)	
			Major	Pitch
¾	10	0.020	0.7682	0.7032
1	8	0.024	1.0220	0.9408
1¼	7	0.024	1.2718	1.1790
1½	6	0.027	1.5246	1.4163
2	4.5	0.050	2.0471	1.9028

Table 18. Overtapping Allowances for ASTM A563 Nuts (ASTM 2015b)

Nominal Diameter (in.)	Threads per inch	Diametrical Allowance, in.	Minor Diameter (in.)		Pitch Diameter (in.)		Minimum Major Diameter (in.)
			Min	Max	Min	Max	
¾	10	0.020	0.6620	0.6830	0.7050	0.7127	0.7700
1	8	0.024	0.8890	0.9140	0.9428	0.9516	1.0240
1¼	7	0.024	1.1190	1.1470	1.1812	1.1908	1.2740
1½	6	0.027	1.3470	1.3770	1.4187	1.4292	1.5270
2	4.5	0.050	1.8090	1.8450	1.9057	1.9181	2.0500

Thread gages, such as plug thread gages, ring thread gages, thread depth gages, thread micrometers, and thread pitch gages, are available for measuring different thread parameters such as diameter, depth, pitch, and angle. However, these gages use contact measurement methods that are expensive, less accurate, have potential for human error, and cause thread damage after use (Rao et al. 2013). On the other hand, Digital Image Analysis (DIA) is a non-contact method. It involves using a microscope, digital camera, and efficient lighting to post-process the images of the threads (Mutambi and Yu 2004). Therefore, the DIA technique was used to measure thread parameters in this research study.

Turn-of-the-nut tightening procedures are currently used for fastening anchor rods onto foundations in ancillary structures (AASHTO 2015; Dexter and Ricker 2002; Garlich and Thorkildsen 2005). This procedure, in a typical double-nut moment connection, involves snug-tightening the anchor nuts followed by an incremental angular tightening of the top nut as per the diameter and grade of the anchor rod. Pretension achieved as a result of the snug-tight condition is variable and depends on many factors, such as the length of the wrench used, personnel strength, friction between the mating threads, and lubrication. Any variation in snug-tight pretension can lead to variable final pretension during turn-of-the-nut tightening. The snug-tight condition also does not have a universally accepted definition and is defined differently in various federal and state highway specifications. As per the AASHTO tightening specifications, snug-tight is defined as the maximum nut rotation resulting from the full effort of one person using a 12 inch long wrench or equivalent (AASHTO 2015; VDOT 2016a). Other reports and implementation documents define snug-tight as 20% to 30% of the final pretension (Dexter and Ricker 2002; Garlich and Thorkildsen 2005; MDOT 2014).

The importance of controlling snug-tight pretension during turn-of-the-nut tightening was pointed out in a recent study conducted by Iowa State researchers in collaboration with the Minnesota Department of Transportation (MnDOT) (Chen et al., 2018). The researchers concluded from the testing of anchor rods on Skidmore Wilhelm that snug-tight pretension is highly variable. The results from the Iowa State study revealed that it is relatively easy to yield smaller diameter anchor rods (< 1½ inch) and under-tighten larger diameter anchor rods (> 1½ inch). It was also concluded that 10% of the yield strength of anchor rods provides a better approximation for the snug-tight condition as compared to other definitions.

This research study involved the measurement of thread parameters such as major diameter, minor diameter, pitch diameter, flank angle, and pitch of five diameters (¾ inch, 1 inch, 1¼ inch, 1½ inch, and 2 inch) of anchor rods and nuts procured from three suppliers. DIA technique and Vernier Calipers were used for measurement. The thread parameter measurements were compared with the allowable tolerances, as shown in Table 17 and Table 18. The second phase of the study consisted of an investigation of the effect of variable wrench length and force applied on the variation of snug-tight pretension in a double nut moment connection. Two diameters (1 inch and 2 inch) of anchor rods were snug-tightened by different participants using variable-length wrenches.

6.3 Evaluation of Thread Fabrication Tolerance

6.3.1 Thread Terminology

There are two types of threads: internal and external. Threads on a bolt, rod, or screw are referred to as 'external threads' whereas threads on a nut are referred to as 'internal threads'. Threads have a triangular profile with the top of the groove known as the crest and the bottom of the groove known as the root. The flanks are defined as the straight sides connecting the adjacent root and crest. The distance measured perpendicular to the axis of the bolt or nut between the adjacent root and crest is known as the thread height. The distance measured parallel to the axis of the bolt or nut between corresponding points on adjacent thread surfaces is known as the thread pitch. The flank angle is defined as the angle between a flank and the axis that is perpendicular to the bolt or nut axis. The thread parameters, like thread pitch and thread height, vary with the diameter. The thread profile for a typical bolt and nut can be seen in Figure 59.

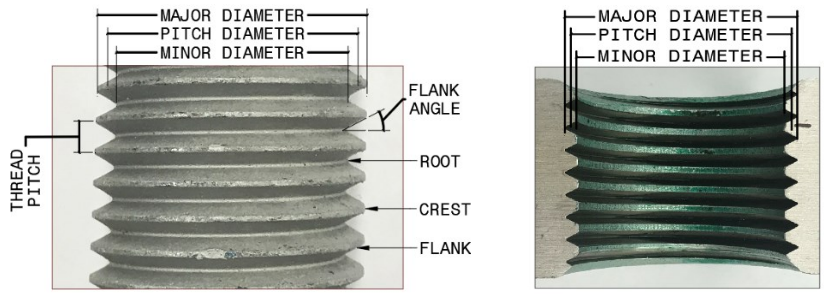

Figure 59. Thread Terminology for the bolt (left) and nut (right)

There are three types of diameters corresponding to external and internal threads: major, minor, and pitch. The major diameter is the largest diameter measured between the crests for the external threads and measured between the roots for the internal threads. The minor diameter is the smallest diameter measured between the roots for the external threads and measured between the crests for the internal threads. The pitch diameter is defined as the diameter of an imaginary cylinder that passes through the thread surface such that the distance between the adjacent flanks intersecting at the crest and the distance between the adjacent flanks intersecting at the root are equal (Fastenal 2009). The pitch diameter should be approximately halfway between the major and minor diameters.

Three types of thread series are commonly used in structural engineering applications: Unified Coarse (UNC), Unified Fine (UNF), and 8 thread (8-UN). There are six classes of thread fit specified within each thread series: 1A, 1B, 2A, 2B, 3A, and 3B. A and B are symbols assigned for external and internal threads, respectively. Thread fit is denoted by the number next to the A and B symbols. The higher number refers to a tighter fit. Thread combination 2A/2B is most commonly used for industrial and commercial applications (Fastenal 2009).

6.3.2 Methodology

Five diameters (¾ inch, 1 inch, 1¼ inch, 1½ inch, and 2 inch) of anchor rods and anchor nuts were procured from three suppliers. Threads of the procured anchor rods and nuts were produced by rolling and were hot-dip galvanized. The anchor rods were grade 55 and were 12 inch in length. Three measurements of the thread parameters were taken along the length of the anchor rod. A mix of ASTM A563 grade DH and ASTM A194 grade 2H anchor nuts were procured based on availability (ASTM 2015b, 2016). However, the galvanization and overtapping tolerances are identical for both types of nuts. Three heavy hex nuts of each diameter were cut in half using a band-saw, and thread parameter measurements were taken for one half of each nut.

Five thread parameters (major diameter, minor diameter, pitch diameter, flank angle, and pitch) were measured for each anchor rod and anchor nut specimen. The measured values were compared to the specified ASTM tolerances in order to study the thread fit and the gaps between mating threads. A 5MP digital microscope (ViTiny Model: UM12) with measurement functions and a resolution of 0.1 mm (0.004 inch) was used for measuring the five thread parameters. The microscope LED lights and other external lighting were used to improve image clarity, improve edge detection, and reduce reflection noise. The major diameter of the rod and the minor diameter of the nut were measured using 24 inch Fowler Electronic Vernier Calipers due to the limited field of view as a result of the high magnifying power of the microscope. The rest of the thread parameters (thread pitch, thread height, and flank angle) were measured using the digital microscope.

Anchor Rods

The experimental procedure for the measurement of thread parameters on anchor rods was as follows:

1. The outside jaws of the Fowler Electronic Vernier Calipers were first used to measure the major diameter of the anchor rod at one location along the length.
2. A target calibrator was used to calibrate the 5MP ViTiny microscope lens at the mid-height of the anchor rod.
3. The thread height, thread pitch, and flank angle of the anchor rod were measured. The thread height measurement of a specimen under a microscope is shown in Figure 60.

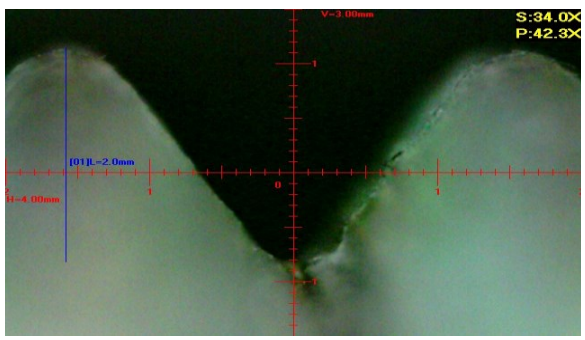

Figure 60. Measurement of the thread height of a specimen under the microscope

4. The thread pitch measured in Step 3 and the major diameter measured in Step 1 were further used to calculate the pitch diameter. The expression for pitch diameter in terms of the major diameter and the pitch was derived using the basic thread profile given in ASME B1.1 (see Equation 6) (ASME, 2003). The assumption of a 30˚ flank angle was used while deriving the expression. This assumption was valid because the flank angle measurement variations during this study were within +/- 0.25˚ and, therefore, have a negligible effect on the derivation of the expression.

$$\text{Pitch Diameter} = \text{Major Diameter} - 2 \times \text{Pitch} \times (0.32475953)$$

Equation 6. Equation for finding out pitch diameter of anchor rods

5. Two times the thread height was subtracted from the major diameter calculated in Step 1 to calculate the minor diameter of the anchor rod.
6. Steps 1 to 5 were repeated for two other locations on the same anchor rod. The average of the thread parameter measurements at the three locations was calculated.
7. The same procedure (steps 1-6) was repeated for the other diameter anchor rods and suppliers.

Anchor Nuts

The experimental procedure for the measurement of thread parameters on anchor nuts was as follows:

1. The inside jaws of the Fowler Electronic Vernier Calipers were used to measure the minor diameter of a half-cut anchor nut at a particular location.
2. Steps 2 and 3, similar to the anchor rod procedure involving calibration and measurement of thread height, thread pitch, and flank angle, were performed (see Figure 61).

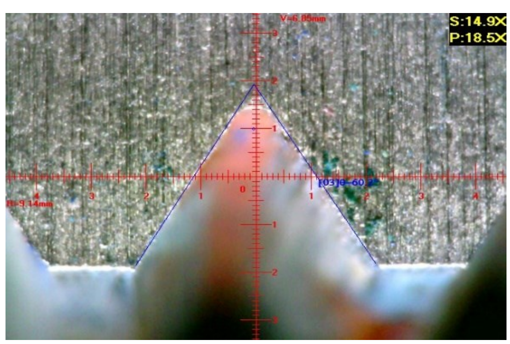

Figure 61. Measurement of the flank angle of a specimen under the microscope

3. The relationship between the thread pitch and minor diameter derived using the basic thread profile given in ASME B1.1 was further used to calculate the pitch diameter (see Equation 7) (ASME, 2003).

$$\text{Pitch Diameter} = \text{Minor Diameter} + \left(2 \times \text{Pitch} \times (0.54126588 - 0.32475953)\right)$$

Equation 7. Equation for finding pitch diameter of anchor nuts

4. Two times the thread height was added to the minor diameter calculated in Step 1 to calculate the major diameter of the anchor nut.
5. Steps 1 to 4 were repeated for cut halves of the two other anchor nuts. The average of the thread parameter measurements from the three nuts was calculated.
6. The same procedure (steps 1-5) was repeated for the other diameter anchor nuts and suppliers.

6.3.3 Results and Discussion

The average measurements of the thread parameters for different diameters of the anchor rods from each supplier and their variation from the maximum allowed tolerances are shown in Table 19, Table 20, and Table 21. The major diameter and pitch diameter for all the anchor rods from the three suppliers were found to be within the allowable tolerances. The negative percentage variation as shown in Table 19, Table 20, and Table 21 indicates that the major diameter and pitch diameter of all the tested specimens were less than the maximum allowed tolerances. There are no tolerances specified for minor diameter in ASTM F1554 (ASTM 2015a). Also, the flank angle for all the test specimens was found to be close to 30˚ with a variation of +/- 0.25˚.

Table 19. Measured thread parameters for anchor rods from Supplier 1

Diameter (in.)	Average Minor Diameter (in.)	Average Flank Angle (˚)	Major Diameter		Pitch Diameter	
			Average (in.)	Variation from the maximum tolerance (%)	Average (in.)	Variation from the maximum tolerance (%)
¾	0.6289	30.15	0.7470	-2.76	0.6831	-2.86
1	0.8355	30.25	0.9930	-2.84	0.9137	-2.88
1¼	1.0618	30.00	1.2350	-2.89	1.1404	-3.28
1½	1.3188	30.15	1.4920	-2.14	1.3744	-2.96
2	1.7067	30.10	1.9980	-2.40	1.8484	-2.86

Table 20. Measured thread parameters for anchor rods from Supplier 2

Diameter (in.)	Average Minor Diameter (in.)	Average Flank Angle (˚)	Major Diameter		Pitch Diameter	
			Average (in.)	Variation from the maximum tolerance (%)	Average (in.)	Variation from the maximum tolerance (%)
¾	0.6205	30.20	0.7465	-2.82	0.6826	-2.93
1	0.8419	30.05	0.9915	-2.98	0.9097	-3.31
1¼	1.0703	29.80	1.2435	-2.23	1.1540	-2.12
1½	1.2678	29.95	1.5040	-1.35	1.3864	-2.11
2	1.6888	30.05	1.9880	-2.89	1.8371	-3.45

Table 21. Measured thread parameters for anchor rods from Supplier 3

Diameter (in.)	Average Minor Diameter (in.)	Average Flank Angle (˚)	Major Diameter		Pitch Diameter	
			Average (in.)	Variation from the maximum tolerance (%)	Average (in.)	Variation from the maximum tolerance (%)
¾	0.6535	30.15	0.7480	-2.63	0.6815	-3.08
1	0.8464	30.15	0.9960	-2.54	0.9142	-2.83
1¼	1.0649	30.10	1.2460	-2.03	1.1539	-2.13
1½	1.2814	30.25	1.4940	-2.01	1.3789	-2.64
2	1.6762	29.90	1.9990	-2.35	1.8456	-3.01

The average variation of the thread parameters from the allowed tolerances for the different diameter of the anchor nuts procured from each supplier are shown in Table 22, Table 23, and Table 24. The minor diameter measurements were found to be within the allowable tolerances for all of the test specimens except the ¾ inch diameter anchor rod from Supplier 3, which was off by

0.96% (see Table 24). The pitch diameter of 10 out of 15 test specimens was more than the allowable tolerance. The maximum deviation observed was 1.26% for 1¼ inch diameter anchor rod from Supplier 3 (see Table 24).

Table 22. Measured thread parameters for anchor nuts from Supplier 1

Diameter (in.)	Average Flank Angle (˚)	Major Diameter		Pitch Diameter		Minor Diameter	
		Average (in.)	Variation from the minimum (%)	Average (in.)	Variation from the tolerance range (%)	Average (in.)	Variation from the tolerance range (%)
¾	29.93	0.7937	3.07	0.7143	0.22	0.6677	Within range
1	29.92	1.0427	1.83	0.9540	0.25	0.8983	
1¼	30.15	1.3087	2.73	1.2048	1.18	1.1355	
1½	30.18	1.5369	0.65	1.4242	Within	1.3532	
2	30.07	2.0881	1.86	1.9281	0.52	1.8242	

Table 23. Measured thread parameters for anchor nuts from Supplier 2

Diameter (in.)	Average Flank Angle (˚)	Major Diameter		Pitch Diameter		Minor Diameter	
		Average (in.)	Variation from the minimum (%)	Average (in.)	Variation from the tolerance range (%)	Average (in.)	Variation from the tolerance range (%)
¾	29.83	0.8014	4.08	0.7101	Within	0.6623	Within range
1	30.15	1.0496	2.50	0.9563	0.49	0.9000	
1¼	29.93	1.2977	1.86	1.1960	0.43	1.1323	
1½	30.13	1.5539	1.76	1.4303	0.08	1.3570	
2	30.13	2.0732	1.13	1.9120	Within	1.8160	

Table 24. Measured thread parameters for anchor nuts from Supplier 3

Diameter (in.)	Average Flank Angle (˚)	Major Diameter		Pitch Diameter		Minor Diameter	
		Average (in.)	Variation from the minimum (%)	Average (in.)	Variation from the tolerance range (%)	Average (in.)	Variation from the tolerance range (%)
¾	30.08	0.7718	0.23	0.7013	-0.52	0.6557	-0.96
1	30.02	1.0365	1.22	0.9580	0.67	0.9000	Within range
1¼	29.87	1.3047	2.41	1.2058	1.26	1.1393	
1½	30.05	1.5693	2.77	1.4381	0.63	1.3560	
2	30.08	2.0515	0.07	1.9117	Within	1.8100	

The major diameter measurements were found to be more than the minimum specified tolerance for all of the 15 test specimens from the three suppliers. There were no maximum tolerances specified for the major diameter. However, a maximum variation of 4.08% from the minimum tolerance was observed for the ¾ inch anchor rods from Supplier 2 (see Table 23). The flank angle variations were negligible and varied in the range of 29.8˚-30.18˚.

The major diameter for both the anchor rods and the anchor nuts were within the allowable tolerances. The measured major diameters of the anchor nut specimens were 1-4% larger than the minimum allowable tolerances and the major diameter of the anchor rod specimens were 2-3% smaller than the maximum allowable tolerances. Since the measured thread parameters for the tested anchor rods and nuts were within allowable tolerances, it can be concluded that the thread tolerances are unlikely to contribute to any nut loosening under vibrations.

6.4 Variation in Snug-tight Pretension

6.4.1 Experimental Test-setup

The tightening of an anchor rod in a double-nut moment connection on a typical ancillary structure was simulated in the laboratory. For this purpose, grade 55 anchor rods with 1 inch and 2 inch diameters were snug-tightened on ASTM A36 steel base plates (ASTM 2014a). The base plates were 24 inch long and 12 inch wide. One inch and 2 inch anchor rods were used to represent behavior of smaller diameter and larger diameter anchor rods used in the industry, respectively. ASTM A194 2H heavy hex nuts along with ASTM F436 round washers were used throughout the testing (ASTM 2016, 2018c).

The base plate thicknesses were equal to the diameter of the anchor rods, representative of the common industry practice. Each base plate was fastened to two I-shaped beam stubs

(W27x217) using 7/8 inch diameter A490 bolts. The beam stubs were further connected to the strong floor of the laboratory. Each anchor rod was passed through a predrilled hole in the center of the base plate. The top nut was snug-tightened using an adjustable length ratchet. The bottom nut was prevented from rotating while tightening by using an adjustable wrench clamped to the bottom of the base plate. The test-setup for snug-tightening of a 2 inch anchor rod is shown in Figure 62.

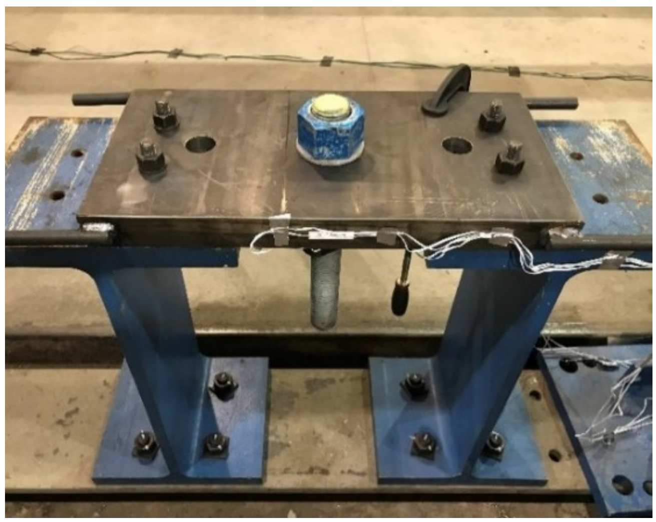

Figure 62. Test-setup for snug-tightening

6.4.2 Instrumentation and Calibration

Each base plate was instrumented with bolt strain gages to measure the induced compression force in the base plate during tightening. Eight bolt strain gages (Tokyo Sokki Kenkyujo Co., Ltd., Model: BTM-6C) were placed inside 5/64 inch predrilled holes below the centroid of the washer area around the rod hole such that the gage center was at mid-thickness of the base plate (see Figure 63). This method ensured the effective measurement of maximum compressive strains during tightening. The compressive strains in the plate were measured and recorded using a Campbell Scientific CR5000 data logger. After the instrumentation of bolt strain gages, each base plate was calibrated in compression using a 300 kip capacity Universal Testing

Machine (UTM) from Satec Sytems, Inc. (Model M300WHVL). The base plates were loaded in compression using nuts and washers at the top and bottom to simulate the boundary conditions during the snug-tightening process. A 'strain-vs-force' calibration curve was made for each base plate. The force in the base plate was calculated corresponding to the induced compressive strains during tightening using the calibration curve. This calculated force was further divided by the tensile stress area of the rod to find the pretension in the anchor rod.

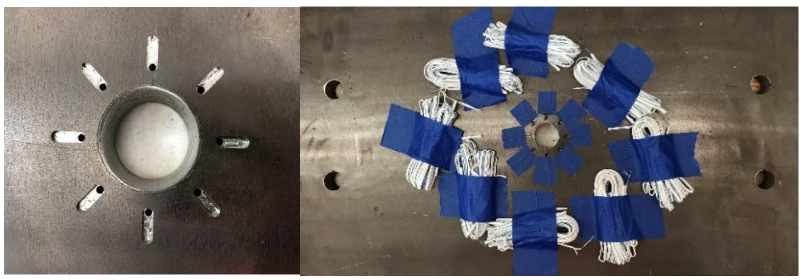

Figure 63. Predrilled holes for bolt strain gages (left) and instrumented bolt strain gages (right)

6.4.3 Experimental Procedure

To capture the effect of varying levels of personnel strength and wrench length on the final snug-tight pretension in a double-nut moment connection, multiple participants were asked to snug-tighten the anchor rods using variable adjustable length ratchets (E-Z Red model: EZRMR1X and Titan Tools model: 12073, 12074). The participants were asked to read different definitions of snug-tight condition provided in various specifications and implementation documents prior to tightening (AASHTO, 2015; Dexter & Ricker, 2002; Garlich & Thorkildsen, 2005; MDOT, 2014; VDOT, 2016). The ratchet lengths were chosen as per the typical available open-end wrench lengths for a particular diameter of the nut. The wrench lengths used during the tightening are shown in Table 25.

Table 25. Wrench lengths used for tightening anchor rods

Anchor Rod Diameter (in.)	Wrench Length (in.)
1	12, 16, 20
2	24, 32, 40

6.4.4 Results

1 inch anchor rods

A total of 19 participants snug-tightened the 1 inch diameter anchor rod. The variation in the snug-tight pretension of 1 inch anchor rod due to different wrench lengths and applied torque is shown graphically using a whisker chart in Figure 64. The overall variation observed was in the range of 8.5 ksi to 63 ksi. The variation in axial stress increased with the increase in wrench length due to the additional leverage during tightening due to the longer wrench (see Figure 64). Snug-tight pretension was found to be more than the specified yield strength of 55 ksi when the 20 inch wrench was used. The smallest variation of axial stress in the rod was 15% to 79% of F_y (55 ksi) when a 12 inch wrench length was used. Therefore, it can be concluded that a 12 inch wrench would produce better results as compared to the other lengths, taking into account the least variation and that no yielding of the anchor rods occurred using this wrench.

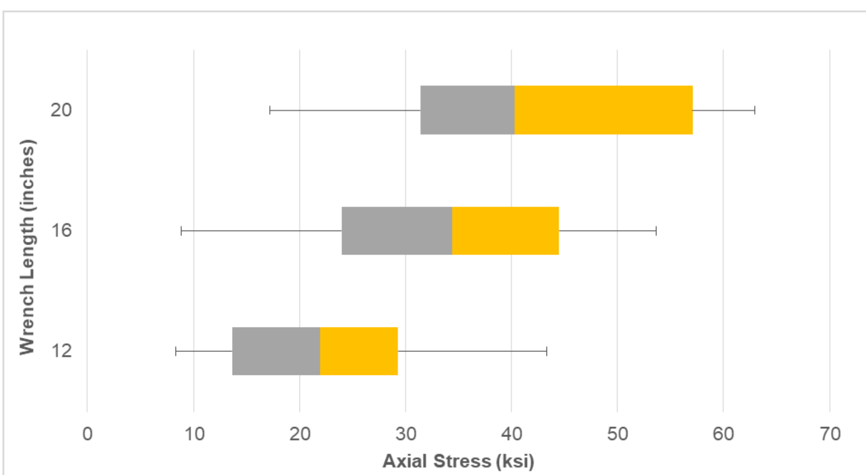

Figure 64. Variation of snug-tight stress in a 1 inch anchor rod

2 inch anchor rods

A total of 16 participants snug-tightened the 2 inch diameter anchor rod. The variation in the snug-tight pretension of 2 inch anchor rods due to different wrench lengths and applied torque is shown graphically using a whisker chart in Figure 65. The overall axial stress variation of 4 to 21 ksi was approximately 1/3rd of the variation in 1 inch anchor rod. The difference in variation can also be seen from the statistical variation shown in the whisker charts in Figure 64 and Figure 65. This difference was primarily due to the additional force required to tighten the larger 2 inch anchor rod, which is approximately four times larger in tensile area as compared to the 1 inch anchor rod. The median and the range of stress increased with the increase in the wrench length, similar to the results of the 1 inch anchor rod. The axial stress ranged from 7.5% to 25% of F_y (55 ksi) for the 24 inch wrench. The maximum axial stress produced was less than half the specified yield strength of 55 ksi. The least variation in stress for the 2inch anchor rod was observed when a 24 inch wrench was used (see Figure 65).

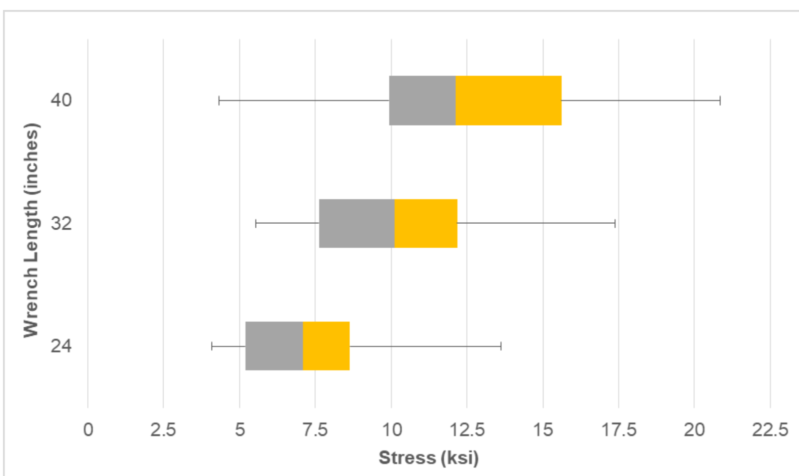

Figure 65. Variation of snug-tight stress in a 2 inch anchor rod

The recommended snug-tight pretension of 20-30% of final pretension (9-13.5 ksi) as per the FHWA specifications and NCHRP report 469 was found to be close to the range of snug-tight stress observed during the tightening of 1 inch and 2 inch anchor rods using 12 inch and 32 inch wrench lengths, respectively (see Figure 64 and Figure 65). Therefore, it can be concluded that 12-inch long wrench and 32-inch long wrench should be used for effective tightening of grade 55, 1-inch and grade 55, 2-inch anchor rods, respectively taking into account the relatively smaller stress variation along with the overlapping of the variation with the recommended snug-tight pretension.

Due to the random nature of the snug-tight definitions, along with the potential for large overall variation in the snug-tight pretension as shown in the results, it is highly likely that there will be either over-tightening of small-diameter anchor rods or under-tightening of large-diameter anchor rods without specific guidelines. This variation in snug-tight pretension can affect the final pretension of the connection. Any reduced final pretension or yielding can potentially contribute to the loosening of the anchor nuts under wind-induced vibrations.

6.5 Conclusions

Dimensional parameters of anchor rods tested in this study were, for the most part, found to be within the specified ASTM thread tolerances. The major diameter and minor diameter for the anchor nuts were within the specified ASTM tolerance range whereas the pitch diameter for two thirds of the anchor nuts were out-of-tolerance. Additionally, the test results indicated that the major diameter of the anchor nuts were 1-4% larger than the minimum allowable tolerance and the major diameter of the anchor rods was 2-3% smaller than the maximum allowable tolerance. Since the thread parameters were within allowable tolerances for anchor rods and nuts, it was concluded that nut loosening is unlikely to occur due to tolerance related issues.

The variable nature of the snug-tight pretension due to different wrench length and personnel strength was observed during the snug-tight tightening study. The variation in snug-tight pretension of a 1 inch anchor rod was found to be in the range of 8.5 to 63 ksi. Snug-tight pretension control is important to prevent any under-tightening of larger diameter anchor rods and yielding of smaller diameter anchor rods. Twelve inch and 32 inch wrench lengths were found to be appropriate for snug-tightening 1 inch and 2 inch anchor rods, respectively. The use of an appropriate wrench length for a specific anchor rod diameter will reduce the chances of under-tightening, yielding, and the potential for loosening under such conditions.

CHAPTER 7: Conclusions, Recommendations and Future Work

Chapter 7 consists of conclusions and recommendations from the results of experimental testing described in Chapters 3, 4, 5, and 6. The conclusions and recommendations have been provided in a sequential order of the chapters in section 7.1 and 7.2, respectively. Section 7.3 enlists the future work pertaining to the field of anchor nut loosening in ancillary structures. Section 7.4 mentions the contributions to the field of structural engineering as a result of the research conducted.

7.1 Conclusions

Three potential causes of anchor nut loosening on ancillary structures were investigated as part of this research which include improper tightening procedures, wind-induced vibrations, and thread fabrication tolerance. Apart from anchor nut loosening, revisions and additions to the tightening procedures for anchor rod tightening were also proposed. Based on the results from the tightening study on double-nut moment connections, tightening study on single-nut connections, field monitoring, large-scale vibration testing, small-scale-vibration testing, thread tolerance study, and snug-tight study, the following conclusions are made:

1. The current tightening procedures for double-nut moment connections specified in the AASHTO, FHWA, and VDOT implementation documents consist of some inconsistencies and discrepancies:
   a) The minimum installation pretension for grade 105 anchor rods is required to be 0.6 times the minimum specified tensile strength as per the FHWA tightening guidelines and NCHRP 469 recommendations. However, increasing this value to $0.7F_u$ results in a P/F_y ratio of 83% for grade 105 rods, which is consistent with the other anchor rod

grades (36 and 55) and also close to the recommended minimum pretension range of 85-100% F_y for structural connections subjected to dynamic loading.

b) At present, AASHTO specifications and FHWA guidelines recommend the same amount of nut rotations for grade 55 and grade 105 anchor rods. However, it was observed during the tightening study that following the current recommended nut rotations leads to yielding of grade 105 anchor rods and under-tightening of grade 55 anchor rods. In order to prevent such cases of inadequate tightening or yielding, separate nut rotations have been recommended for grade 55 and grade 105 anchor rods as revisions to the current AASHTO tightening specifications.

c) There is minimal tightening data related to small diameter anchor rods (< 1½ inch), and, the existing AASHTO specifications and FHWA guidelines also group all the rods with diameters less than 1½ inch under one category. Therefore, all the different diameter of anchor rods ranging from ¾ inch to 2 inch were tested as part of the tightening study to cover the entire range of common diameters of anchor rods. It was concluded from the study that all the anchor rods with diameters greater than or equal to 1 inch require the same amount of nut rotations to achieve the minimum installation pretension. Therefore, the new recommended two categories of anchor rod diameters are less than 1inch and greater than or equal to 1inch in comparison to the present grouping of anchor rods, which categorizes the anchor rods into two groups: less than or equal to 1.5 inch and greater than 1.5 inch.

2. It was concluded from the single-nut connection tightening study that a larger torque value (250 ft-lb) as compared to the manufacturer recommended value of 150-200 ft-lbs was required for proper tightening of anchor nuts. The anchor nuts in single-nut connections

are prone to loosening under vibrations due to concrete wear under the T-base or the base plate. The new recommended torque value of 250 ft-lb ensured an average pretension of 0.6*F_u (45 ksi) in the grade 55 tested anchor rods. It was also observed that lubrication and incremental tightening in a star tightening pattern facilitates the ease of tightening and better distributes the stresses in the anchor rods.

3. During the field monitoring of the cantilevered traffic signal and the luminaire, there was evidence of stresses and accelerations due to vibrations in both the principal directions of the instrumented ancillary structures in spite of the majority of winds blowing from one direction. These bi-directional stresses and accelerations due to vibrations are suggestive of occurrence of wind loading phenomenon like vortex-shedding and galloping in conjunction with the natural wind gusts.

   a) The measured bending pole stresses due to vibrations during the field monitoring were converted into anchor rod stresses due to vibrations. As per the anchor rod vibration stress data, low vibration stress ranges (<5 ksi) contributed to the maximum number of vibration cycles for the instrumented traffic signal and luminaire during the four-month field monitoring period. The extrapolation of the stress range data revealed that the traffic signal would experience approximately 1.25 million cycles of 4 ksi stress range in one year.

   b) Fundamental in-plane and out-of-plane modes of the mast arm (mode 2 and 3) were found to be dominant modes for the traffic signal as compared to the first and second mode for the luminaire during the four-month field monitoring.

4. It was concluded from the large-scale vibration testing that inadequate tightening (at lower levels of pretension) in combination with wind-induced vibrations in the stress range of 4 to 5 ksi can lead to loosening of anchor nuts on ancillary structures.
   a) The pretension threshold below which anchor nut loosening occurs was found to be 5 ksi. During testing, anchor rods with initial pretension of 2, 3, and 4 ksi became loose within 1.5-3.5 million cycles of 4-5 ksi vibration stress range. Anchor rods with initial pretension of 5 ksi did not become completely loose, even after 20 million cycles of 5 ksi vibration stress range.
   b) The vibration loosening behavior of the anchor nuts was typically divided into 3 stages. The first stage involved small nut rotations accompanied by rapid loss in pretension within the first few thousand cycles. The majority of this initial loss in pretension was during the first few thousand cycles and was primarily due to material yielding or stress relaxation at the thread roots. The second loosening stage consisted of a steady but slow loss of pretension along with small nut rotations. The third and the final stage involved the rapid backing of the nut accompanied by the sudden loss in pretension.
5. The number of cycles to nut loosening along with the overall behavior of the loosening was found to be similar for both the large-scale and small-scale vibration testing. The pretension threshold was found to be 4 ksi during the small-scale vibration testing as compared to 5 ksi during the large-scale vibration testing. Overall, the small-scale vibration testing provided a good validation of the large-scale testing results.
6. The thread parameters including major diameter, minor diameter, and flank angle for the procured anchor rods and anchor nuts from 3 different regional suppliers were found to be within allowable tolerances as per the ASTM F1554 and ASTM A563 standards.

Therefore, it was concluded that nut loosening was unlikely to occur due to thread tolerance related issues. There was no noted occurrence of poor quality of galvanization or overtapping on the threads of the anchor rods and nuts.

7. Snug-tight condition does not have a universally accepted definition and is defined differently in various tightening specifications and guidelines (AASHTO, FHWA, VDOT, NCHRP 469). Any variation in snug-tight pretension can lead a variable final pretension during the turn-of-the-nut tightening procedure. As per the snug-tight study results, snug-tight pretension on the tested grade 55, 1-inch anchor rods was found to be highly variable (10-60 ksi) due to the effect of different wrench lengths, varying interpretation of snug-tight condition and varying physique.
    a) Variation in snug-tight pretension on the tested grade 55, 2-inch anchor rod was found to be 3 times lower than the 1-inch anchor rods due to the larger torque required for tightening as a result of the larger cross sectional area of the 2-inch anchor rod.
    b) The average snug-tight pretension achieved in 1-inch diameter and 2-inch diameter anchor rods using 12-inch and 32-inch wrench length, respectively was found to be close to the recommended snug-tight pretension value (20-30% of the final pretension) given by NCHRP 469 and FHWA guidelines. These wrench lengths also showed lower variation in pretension due to varying physique as compared to the other wrench lengths.

7.2 Recommendations

On the basis of the conclusions from the tightening study on double-nut moment connections, tightening study on single-nut connections, field monitoring, large-scale vibration testing, small-scale-vibration testing, thread tolerance study, and snug-tight study, the following recommendations are made:

1. Current tightening procedures for double-nut moment connections in ancillary structures specified in AASHTO, FHWA, and VDOT specifications need to be revised based on the findings from this study. The new changes, such as regrouping of anchor rod diameters, separation of nut rotations for grade 55 and grade 105 rods, revised recommended nut rotation values, and increased minimum installation pretension for grade 105 rods, will reduce the incidents of over-tightening or under-tightening during the installation of anchor rods in double nut moment connections on ancillary structures. Proposed changes to the current specifications for double-nut connections are shown in Appendix B.
2. There are currently no separate guidelines for tightening single-nut connections on ancillary structures. Single-nut connections are required to be tightened to the same amount as double-nut moment connections as per the FHWA and NCHRP 469 guidelines. The AASHTO specifications recommend tightening single-nut connections to 50% of the recommended nut rotations specified for double-nut connections. Therefore, new tightening procedures for grade 55, 1-inch anchor rods with the incorporation of a specified torque instead of turn-of-the-nut method for ease of tightening especially inside transformer bases have been proposed and are shown in Appendix B.
3. Tightening of the anchor rods in double-nut moment connections to the recommended minimum installation pretension can prevent loosening of anchor nuts in ancillary structures subjected to wind-induced vibrations. Any inadequate tightening with initial pretension less than 5 ksi will result in anchor nut loosening during vibrations. Inadequate tightening can result from improper contact of the levelling nut or the top nut on the base

plate during tightening. To achieve adequate tightening, the following are recommended: proper training of the tightening crew, clean threads from debris or contaminants before tightening, and application of verification torque within 24-48 hours of tightening.

4. The definition of snug-tight condition in the present tightening specifications (AASHTO and VDOT) and tightening guidelines (FHWA and NCHRP 469) can be easily misinterpreted. Therefore, revisions to snug-tight definition are required to reduce the variability associated with snug-tight pretension. According to the results from this research, a 12-inch long wrench and 32-inch long wrench should be used for snug-tightening of grade 55, 1-inch and 2-inch anchor rods in double-nut moment connections, respectively since these wrench lengths on an average produce snug-tight pretension close to the recommended values given by NCHRP 469 and FHWA guidelines.

7.3 Future Work

The following items are suggested for future work in the field of anchor rod connections on ancillary structures:

1. The tightening study as part of this research only looked at anchor rods with diameters less than or equal to 2 inch. Additional tightening data for single-nut and double-nut connections with larger diameter anchor rods (>2 inch) should be gathered for improving the current recommended nut rotations and torque values for installation of anchor rods on ancillary structures.
2. Snug-tight condition at present is vaguely defined and can be easily misinterpreted. Snug-tight study in this research only looked at anchor rods with diameters, 1 inch and 2 inch. A snug-tightening study should be performed on other common anchor rod diameters (¾ inch, 1.5 inch, 2.5 inch, 3 inch, and 4 inch) to get a better understanding regarding the

variation in snug-tight pretension. More snug-tight pretension data should be synthesized for providing a generalized definition of snug-tight condition to reduce the variability associated with snug-tight pretension. A specific guideline for snug-tightening different diameters and grades of anchor rods needs to be developed.

3. Field monitoring as part of this research was conducted for 4 months. Longer field monitoring programs should be conducted in the future to better understand the effect of varying wind patterns, varying seasons, and thermal gradients on the resultant anchor rod stresses. Ancillary structures at different locations (inland vs coastal) should also be field monitored to observe the effect of different wind-loadings on ancillary structures.
4. Based on the results from this research, inadequate tightening was found to be one of reasons for loosening of anchor nuts on ancillary structures. Therefore, there is a need to develop a tightening program for training of installation crews, inspectors, and engineers at the state levels for proper installation and tightening of anchor rods on ancillary structures.
5. Loose anchor nuts are believed to contribute to higher stresses in the anchor rods and reduce the fatigue performance of ancillary structures. However, there has not been enough past research in this area quantifying the effect of completely loose nuts on fatigue performance of ancillary structures. Therefore, large-scale fatigue testing should be conducted to better understand the relationship between loose anchor nuts and fatigue performance of ancillary structures.
6. There has been past analytical research in the field of structural connections showing that yielding or permanent deformation in a connection can result in pretension loss under cyclic loads. Therefore, another area of future experimental research should be focused on

analyzing the effect of permanent deformations on loosening of anchor nuts under vibrations.

7.4 Ph.D. Contributions

The original contributions of this research are as follows:

1. Investigating the causes of anchor nut loosening in ancillary structures and recommending remedial measures.
    a) Prior to this research, the cause of anchor nut loosening was unknown. The results from this research indicated that inadequate tightening, in combination with wind-induced vibrations can lead to anchor nut loosening.
    b) Prior to this research, there was minimal research data pertaining to anchor nut loosening on ancillary structures. Additionally, there was no documented relationship between the installation pretension and vibration stress range that could lead to anchor nut loosening. This research determined the initial pretension threshold below which anchor nut loosening initiates.
    c) This research also involved development of vibration nut loosening curves for grade 55, 1 inch and 1.25 inch diameter anchor rods at different levels of pretension and vibration stress ranges.
2. Review and revisions to the current tightening procedures for single-nut and double-nut moment connections in ancillary structures.
    a) The current tightening procedures for double-nut moment connections specified in AASHTO and VDOT specifications were found to have some discrepancies and inconsistencies, based on the results of this research. Proposed changes were made

to the AASHTO specifications for double-nut moment connections, which would ensure proper tightening of anchor rods without yielding or under-tightening.

b) Single-nut connections are known to be prone to pretension loss under cyclic loads due to the wear of concrete and grout pad. However, there are no guidelines for tightening single-nut connections in either the AASHTO or VDOT specifications. A separate tightening procedure for single-nut connections has been proposed based on the results from this research study. This new procedure incorporates a specified torque rather than the turn-of-the-nut method for tightening because the turn-of-the-nut method is not feasible due to lack of access within a standard transformer base.

3. Expanding the knowledge of wind-induced vibrations in ancillary structures.

    a) This research involved identification of the dynamic characteristics of ancillary structures including dominant modes, damping ratios, and maximum stresses due to vibrations in ancillary structures for both galvanized steel traffic signals and aluminum luminaires. The data and information from this research study will be used for conducting future fatigue and vibration research on ancillary structures.

    b) This research involved full-scale resonance testing of galvanized traffic signal at varying levels of pretension and stress ranges using an eccentric weight motor. The successful full-scale testing demonstrates the effective use of resonance and eccentric weight motors for vibration and fatigue testing of ancillary structures as compared to the relatively slower actuator testing, which has traditionally been performed. Another advantage of resonance testing is the easy detection of onset of failures (weld cracking or loosening of nuts) which can cause a drop in vibrational amplitude during resonance as a result of change in frequency or stiffness.

c) This research involved a novel way of simulating axial vibrations in an anchor rod fastened in a double-nut moment connection in a fatigue-rated UTM. The small-scale vibration testing provided a good validation of the large-scale vibration testing which demonstrates that small-scale vibration testing in ancillary structures can be used in future research projects to increase efficiency.

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APPENDIX A

Tightening Procedures Survey for Contractors and Installation Crew along with responses

The results of the survey are shown in italics below the corresponding question.

1. What tightening methods are used when tightening nuts onto the rods of a transformer base aluminum light pole? Select all that apply.

Responses:

   a. Snug-Tight - *2*
   b. Turn-of-the-Nut (Marking on nuts) - *1*
   c. Calibrated Torque Wrench - 1
   d. Direct Tension Indicator (DTI) - *1*
   e. Other (please explain) – *Battery power impact gun or ¾ inch ratchet until tight*

2. If a torque wrench is used, what is the target torque for 1 inch diameter anchor rod during tightening?

Responses: 150 ft-lb

3. If turn-of-the-nut method is used, what is the target nut rotation for 1 inch diameter anchor rod during tightening?

Responses: 1/3 turn beyond a snug-tight condition as per 2013 AASHTO LTS-6

4. What tool(s) or equipment are used when tightening anchor nuts on transformer bases (e.g socket wrench, hydraulic, pneumatic, slugger wrench, open end wrench, etc.)?

Responses:

Deep sockets, battery impact gun, ratchet, open-end wrench

12" long wrench for tightening as per 2013 AASHTO LTS-6

Socket wrench

Torque wrench

5. Are nuts and/or bolts lubricated prior to tightening? If yes, what lubricant is used?

Responses:

PB Blaster

No lubrication

Type of lubricant is not specified as per AASHTO

6. What methods are used to access the interior of the transformer bases for tightening of the nuts onto to the foundation? What tools are used for this?

Responses:

Ratchet and deep socket

Access through the service door of the transformer base

Short Wrench

7. Are nuts checked for tightness at the end of installation? If yes, how are they checked?

Responses:

Yes, with Impact gun

Tightness is checked by verifying that the correct amount of nut rotation has been achieved

Yes

8. What is the most common grade and diameter of anchor rods/bolts used?

Responses:

1" bolts

Grade 55 anchor bolts. 1" diameter is the most common used anchor bolt size.

1 inch galvanized

Grade 55, 1" dia.

9. What are some common suppliers of transformer bases in your district/state?

Responses:

Atlantic technical, JJM

Akron Foundry.

Atlantic Technical Sales, TST

10. Approximately how many transformer base poles have been tightened in your district/region using these procedures?

Responses:

All

Don't know

11. How often are the nuts on these structures checked for tightness (post-installation inspection)?

Responses:

Every 5 years

No current guidelines for checking the tightness post-installation. However, breakaway devices are to be periodically inspected for corrosion. See 2013 AASHTO LTS-6, Section 12.6.

12. Have any loose nuts been observed in the past? If so, please provide an approximate percentage or frequency of occurrence for these cases.

Responses:

Problems with older poles

Yes. Unknown.

13. Please provide any specifications or reference documents used related to transformer base tightening procedures.

Responses:

AASHTO LTS-6, Section 5.17.5.2

14. Does the Tightening Procedure for the top nuts and top bolts differ from the foundation anchor rods?

    If yes, please explain the differences.

Responses:

Tighten both with an impact gun.

There is not a specific procedure for the top bolts. However, it is likely that same procedure is followed that is specified for the bottom anchor rods

15. Additional comments

Responses:

T-bases are tightened in Virginia and Maryland using a ratchet and socket or using an impact gun.

T-bases are tightened to a manufacturer recommended torque of 150 ft-lb. T-bases are designed to shear close to the bottom. A good reference for tightening procedures is 2013 AASHTO LTS-6.

APPENDIX B

Proposed revisions and additions to the current tightening procedures for double-nut moment connections and single-nut connections (grade 55, 1 inch anchor rods) in AASHTO specifications

The proposed additions and changes to the current tightening procedures for anchor rod connections on highway ancillary structures specified in AASHTO specifications are highlighted in red (AASHTO 2015).

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 **as per the procedure (a). Grade 55, 1-inch anchor bolts in single-nut and transformer base connections shall be pretensioned as per the procedure (b).** Anchor bolts in **other** 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. The most common method of pretensioning anchor bolts is the turn-of-nut method. Top nut rotation requirements to achieve proper anchor bolt pretensioning **in double-nut moment connections** are given in Table C15.6.3-l. **For grade 55, 1-inch anchor bolts in single-nut and transformer base connections, it is recommended to tighten the anchor bolts using a specific torque value as specified in procedure (b).** For **other** 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~~
~~≤1½~~	~~⅙ turn~~	~~⅓ turn~~
~~>1½~~	~~1⁄12 turn~~	~~⅙ turn~~

Anchor Bolt	Nut Rotation beyond Snug-Tight [a,b,c,d]		
Diameter, in.	F1554 Grade 36	**F1554 Grades 55**	**F1554 Grades 105**
<1	**1/6 turn (60°)**	**1/5 turn (75°)**	**1/3 turn (120°)**
≥1	**1/8 turn (45°)**	**1/6 turn (60°)**	**1/4 turn (90°)**

[a.] Nut rotation is relative to anchor bolt. The tolerance is plus ~~**20**~~ **15** degrees (~~1/18~~ 1/24 turn).

[b.] Applicable only to **anchor bolts with UNC threads** in 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.

[d.] **Minimum installation pretension is 50%, 60%, and 70% of minimum specified tensile strength of grade 36, 55, and 105 anchor bolts, respectively.**

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 **and also lead to better stress distribution during installation. Inadequately tightened or loose anchor bolts can lead to redistribution of higher stresses in the other anchor bolts.** As a result, the pretensioned condition is inherently better with respect to the performance of anchor bolts.

Procedure (a)

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).

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. 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.
3. Tum 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 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. 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. 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.)
6. Tighten leveling nuts to a snug-tight condition in a star pattern.
7. 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 a corresponding reference mark on the base plate at each bolt. Then incrementally tum the top nuts using a star pattern until achieving the required nut rotation specified in Table C15.6.3-l. 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 $0.6F_y$ for other bolts)**~~

(F_t = $0.5F_t$ for Grade 36 bolts, $0.6F_t$ for Grade 55 bolts, and $0.7F_t$ for Grade 105 bolts)

8. Retightening of installation by use of torque is recommended within 24-48 hours after bolt tightening to account for any creep in the galvanizing within the threads. The retightening torque is 110 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 2½ 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.**~~ **ASTM F2437 should include DTIs for grade 36, grade 55, and grade 105 anchor bolts in diameters up to 2½ in. with preload of 50%, 60%, and 70% of the minimum specified tensile strength, respectively.** 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.

Single-nut and T-base connections with grade 55, 1-inch anchor bolts are recommended to be pretensioned to a manufacturer recommended torque using a calibrated torque wrench.

Procedure (b)

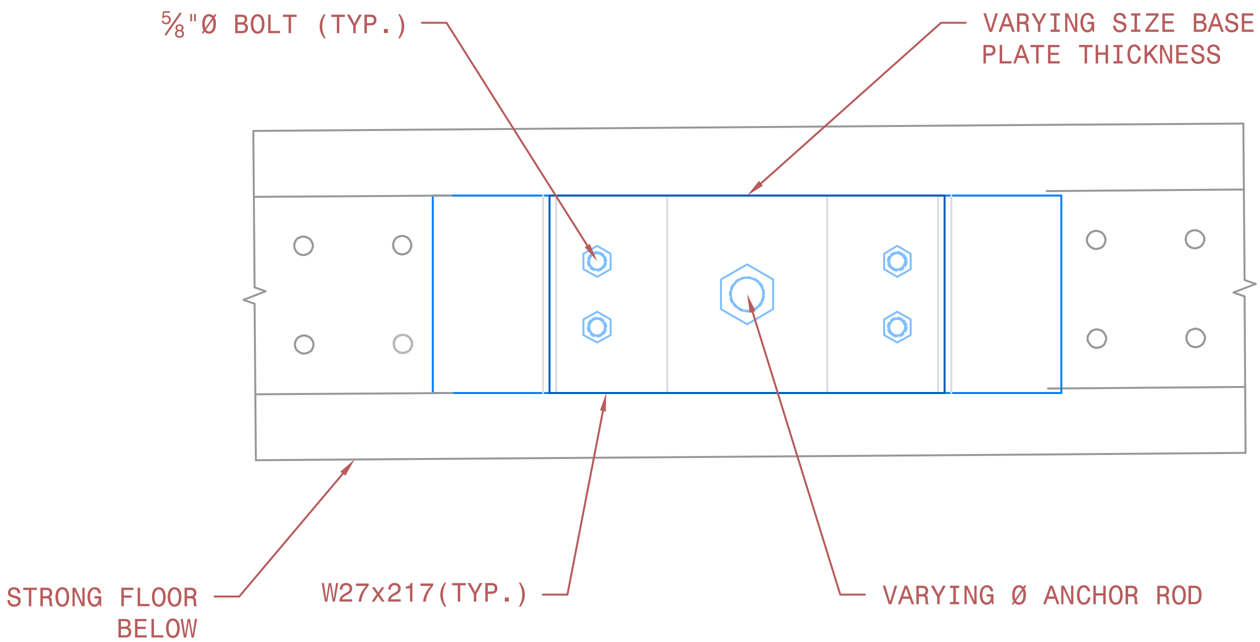
The following procedure should be considered when pretensioning only grade 55, 1-inch anchor bolts in single-nut connections.

1. **A minimum of one nut and one hardened washer shall be provided for each anchor bolt. In the case that flat thick washers are provided by the pole manufacturer, use the flat thick washers for better distribution of load.**

2. **Verify that the nuts can be turned onto the bolts along the full exposed length 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).**
3. **Clean and lubricate the exposed threads of all anchor bolts and nuts. Re-lubricate the exposed threads of the anchor bolts and the threads of the nuts if more than 24 hours has elapsed since earlier lubrication, or if the anchor bolts and nuts have become wet since they were first lubricated.**
4. **The post or end frame shall be plumbed or aligned as shown on the shop drawings. The holes in the base plate/T-base shall pass through the anchor bolts with ease. Place the flat thick washers (if provided) followed by standard hardened washer on the top of the base plate/T-base. Turn the top nuts onto the anchor bolts. Ensure that all the anchor nuts are hand-tight.**
5. **Tighten the top nuts incrementally to the manufacturer recommended torque value for a T-base or other single-nut connections using a calibrated torque wrench. The torque should be applied in a star tightening pattern in at least 3-4 increments for better distribution of loads in the anchor bolts. A star tightening pattern is one in which the nuts on opposite or near-opposite sides of the bolt circle are successively tightened in a pattern resembling a star.**
6. **Use of deep sockets and a long vertical extension is allowed for the ease of tightening. Due to the lack of space inside the T-base, it is challenging to tighten from the access door. A long extension can be passed through the top bolt holes in the T-base and the tightening can be performed using a torque wrench and extension from the top.**
7. **For T-base tightening: after the installation of the T-base, a turn-of-the-nut procedure should be followed for fastening the base plate to the top of the T-base using structural bolts, nuts, and washers provided by the manufacturer.**

APPENDIX C

Experimental Test drawings



PLAN VIEW
(1"=1'-0")

NOTE - L6x6x¾ ANGLE NOT SHOWN FOR CLARITY. SEE ELEVATION VIEW

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200 PATTON HALL
BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT: Self-Loosening of Anchor Nuts

SHEET NOTES:

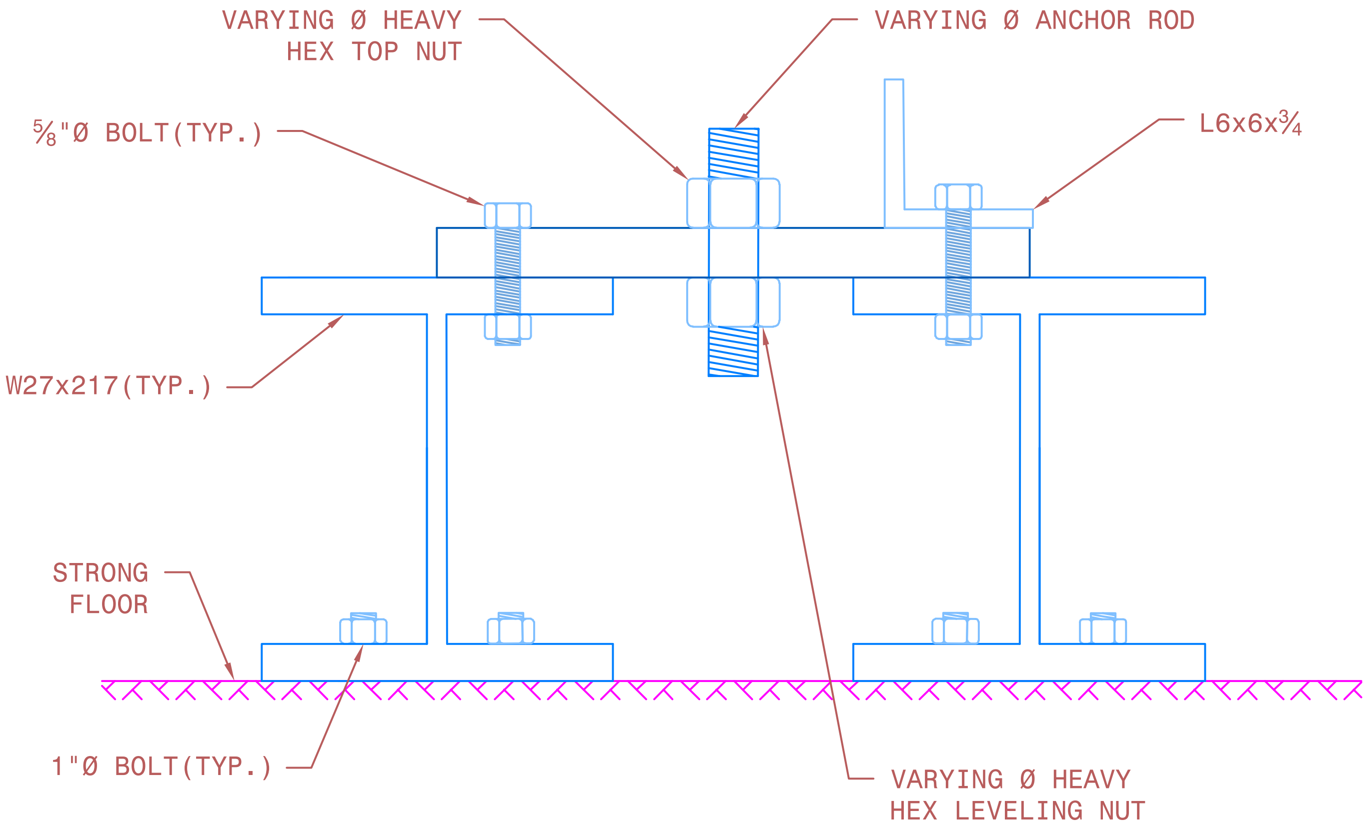
REVISIONS:

NO.	DATE	BY

DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 03/20/2017
PROJECT NO.: Number

SHEET TITLE: Tightening Procedures for Anchor Bolts

SHEET NO.: 1 of 2



ELEVATION VIEW
(1-1/2"=1'-0")

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200 PATTON HALL
BLACKSBURG, VA 24061
P: 540-231-6635

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SHEET NOTES:

REVISIONS:

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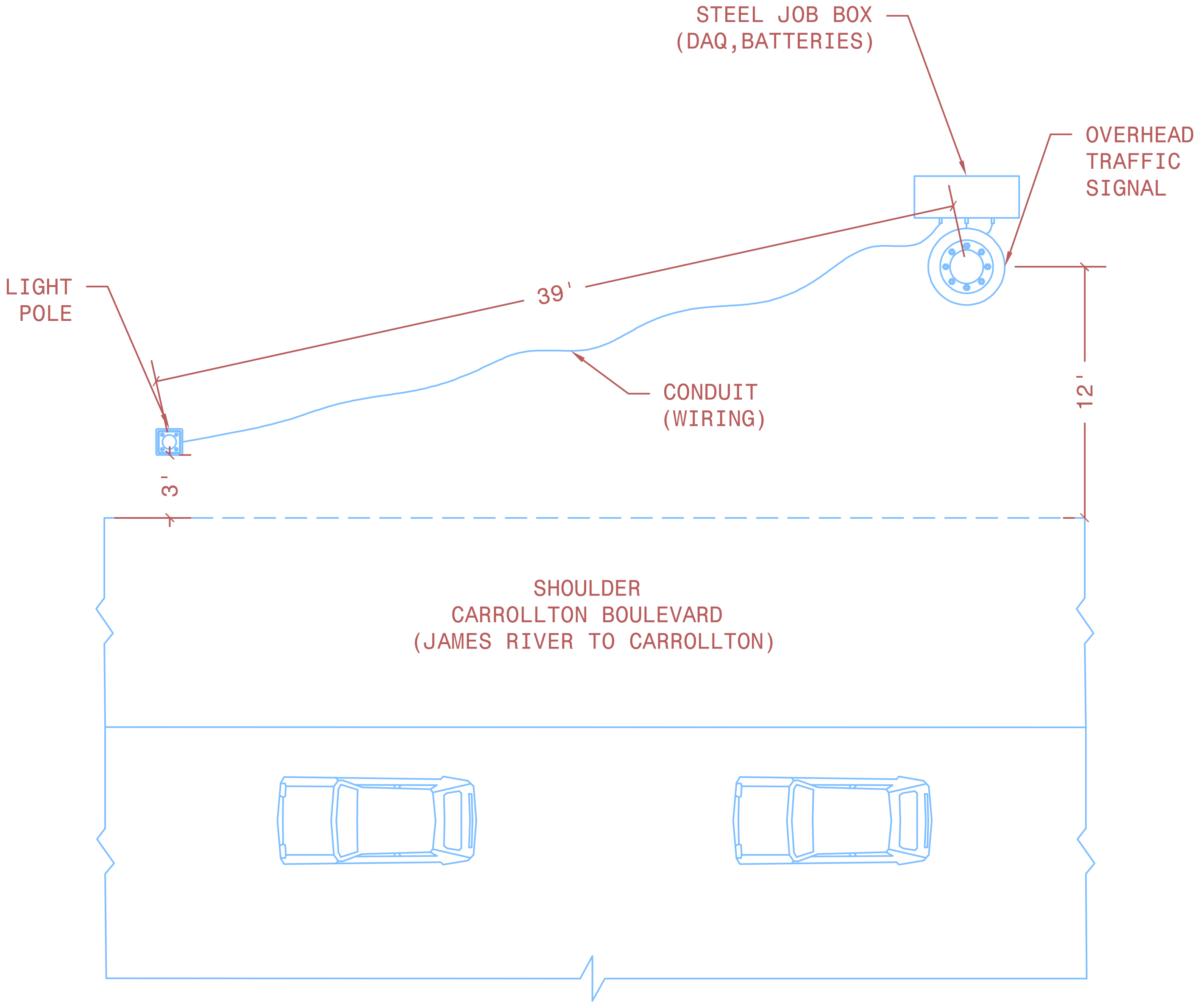
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 03/20/17
PROJECT NO.: Number

SHEET TITLE:
Tightening Procedure for Anchor Bolts

SHEET NO.: 2 of 2



PLAN VIEW
(1/8"=1'-0")

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CHARLES E. VIA JR. DEPARTMENT OF
CIVIL & ENVIRONMENTAL
ENGINEERING
200 PATTON HALL
BLACKSBURG, VA 24061
P: 540-231-6635

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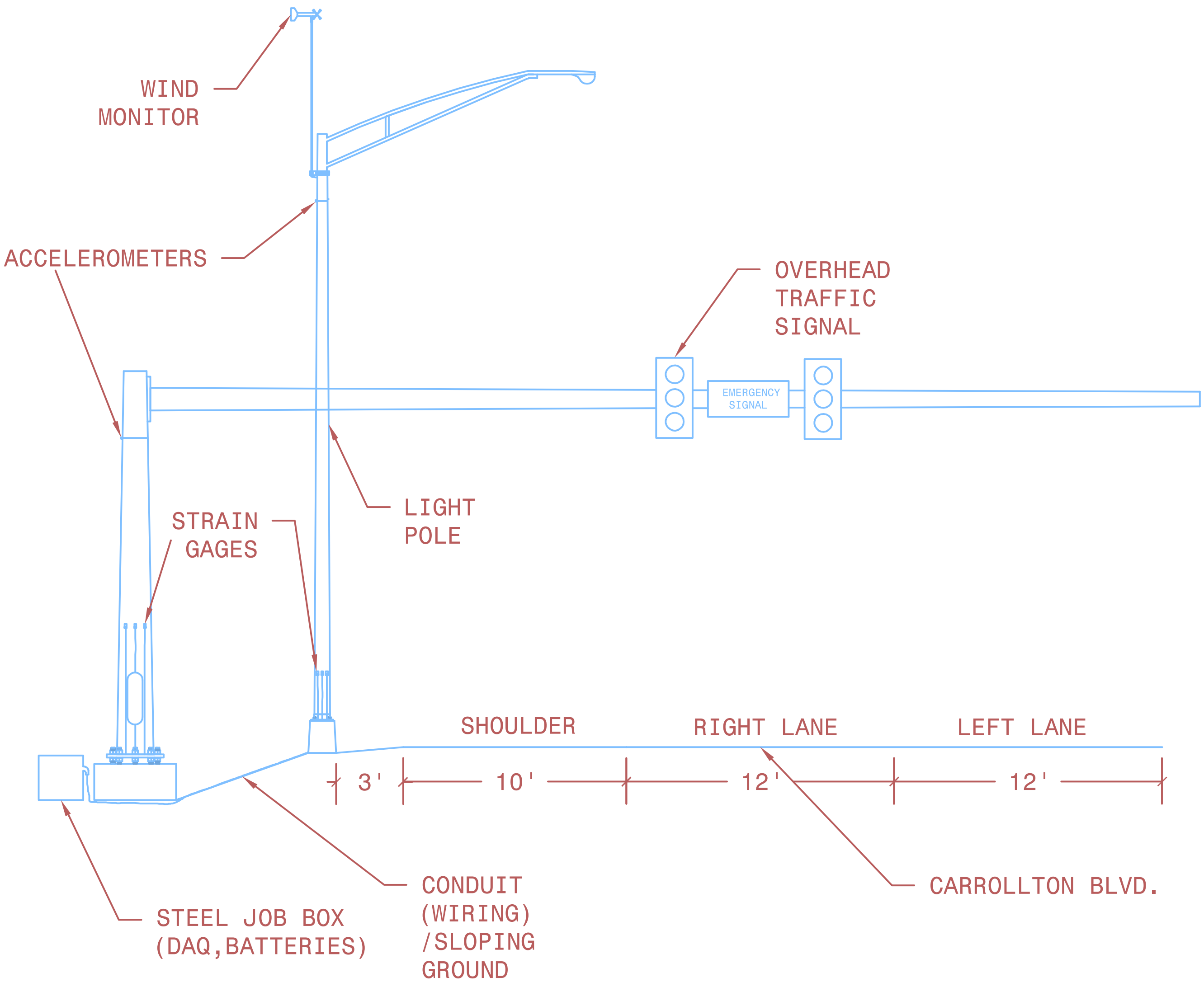
DATE:	02/02/2018
PROJECT NO.:	Number

SHEET TITLE:
Proposed Field Monitoring of Light Pole and Traffic Signal

SHEET NO.: 1 of 2



ELEVATION VIEW
(1/8"=1'-0")

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CHARLES E. VIA JR. DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING
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BLACKSBURG, VA 24061
P: 540-231-6635

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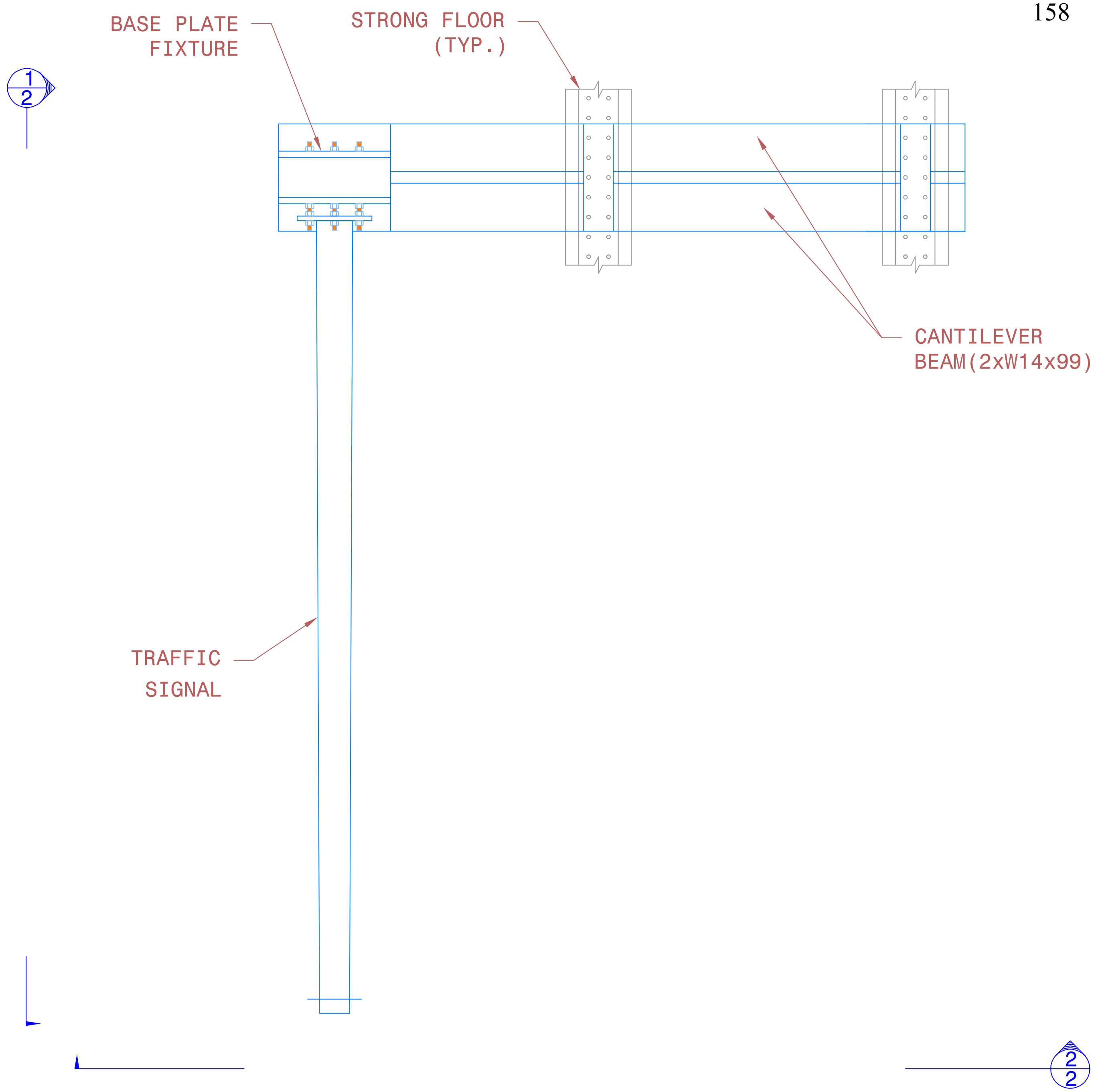
Proposed Field Monitoring of Light Pole and Traffic Signal

SHEET NO.: 2 of 2



1/1 LARGE-SCALE TESTING PLAN VIEW

SCALE - $\frac{1}{4}$"=1'-0"

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CHARLES E. VIA JR. DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING
200 PATTON HALL
BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

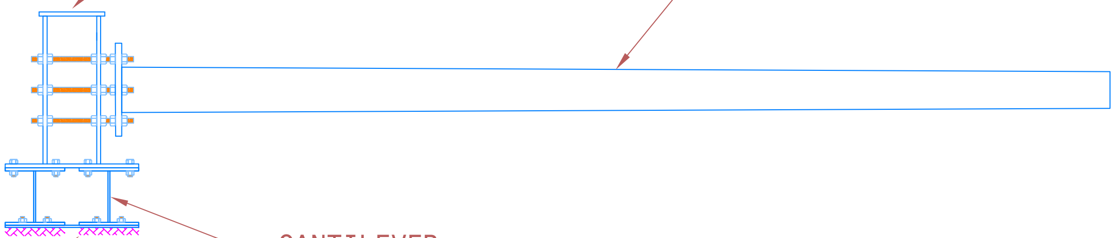
REVISIONS:

NO.	DATE	BY

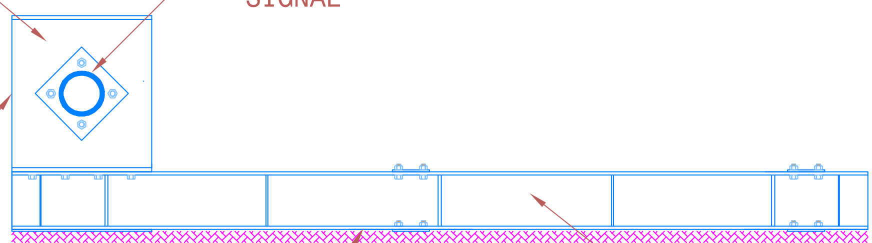
DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	05/22/2018
PROJECT NO.:	Number

SHEET TITLE:
Large-Scale Testing of Steel Traffic Signals

SHEET NO.: 1 of 4



1/2 LARGE-SCALE TESTING SIDE ELEVATION VIEW



2/2 LARGE-SCALE TESTING FRONT ELEVATION VIEW

SCALE - $\frac{1}{4}$"=1'-0"

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ENGINEERING
200 PATTON HALL
BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

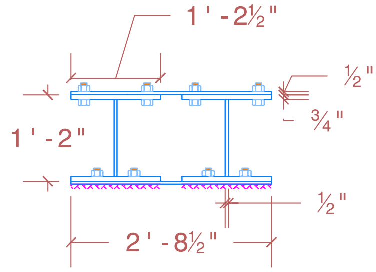
REVISIONS:

NO.	DATE	BY

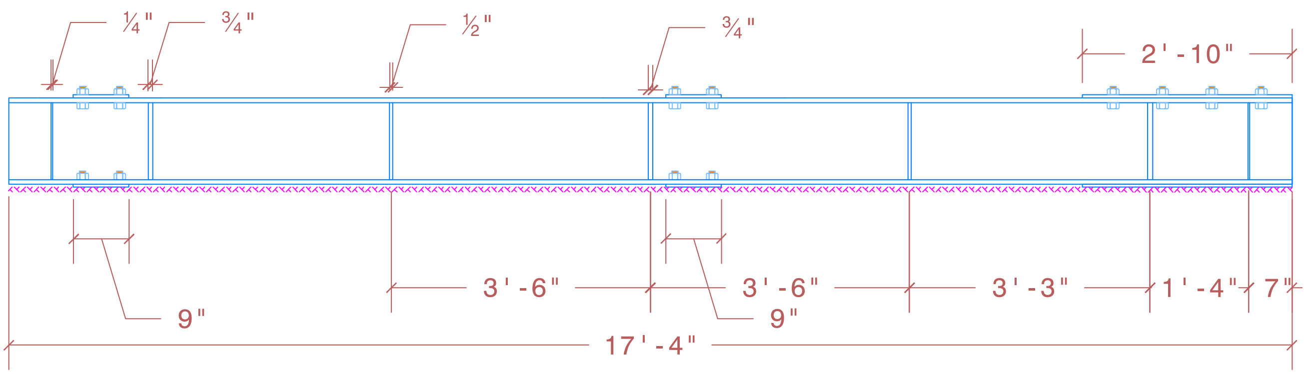
DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 05/22/2018
PROJECT NO.: Number

SHEET TITLE:
Large-Scale Testing of Steel Traffic Signals

SHEET NO.: 2 of 4



1 / 3 CANTILEVER BEAM FRONT ELEVATION VIEW



2 / 3 CANTILEVER BEAM SIDE ELEVATION VIEW

SCALE - $\frac{3}{8}$"=1'-0"

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BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT: Self-Loosening of Anchor Nuts

SHEET NOTES:

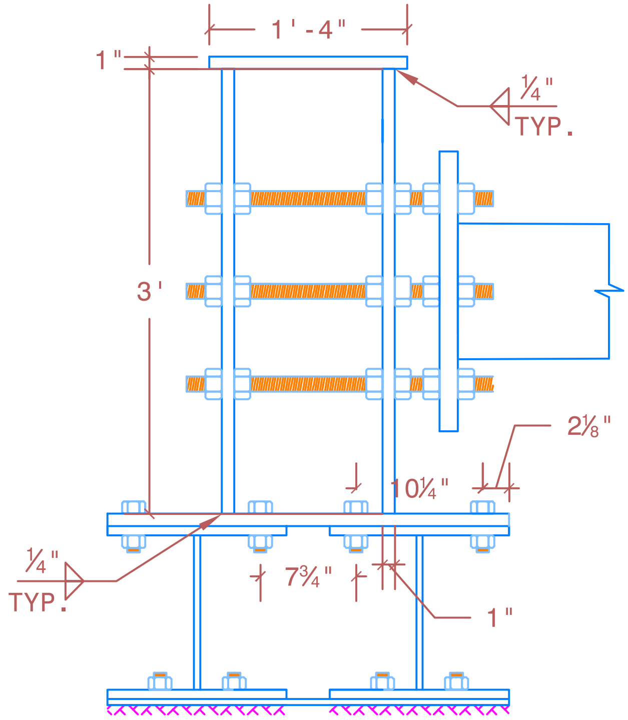
REVISIONS:

NO.	DATE	BY

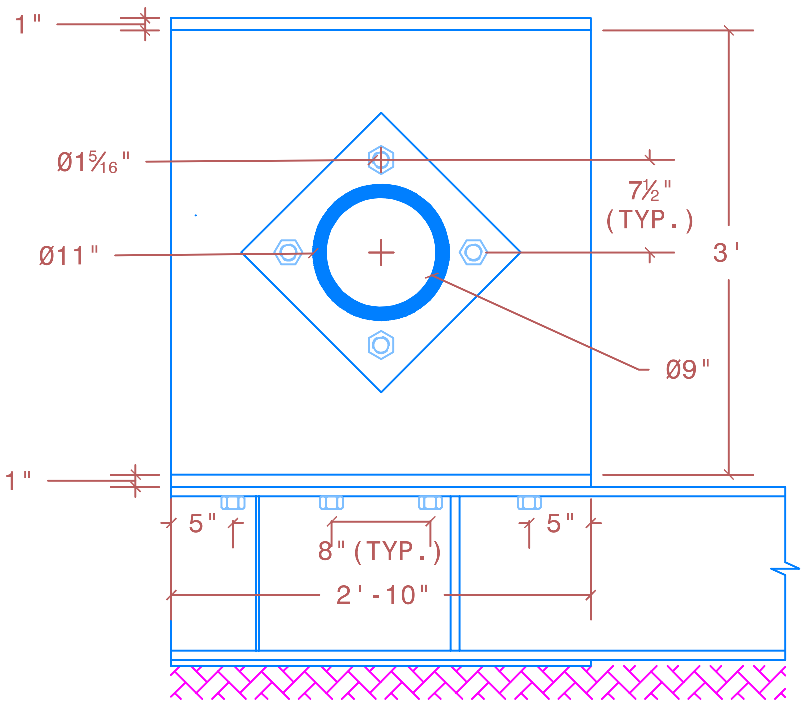
DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	05/22/2018
PROJECT NO.:	Number

SHEET TITLE: Large-Scale Testing of Steel Traffic Signals

SHEET NO.: 3 of 4



1/4 BASE PLATE FIXTURE FRONT ELEVATION VIEW



2/4 BASE PLATE FIXTURE SIDE ELEVATION VIEW

SCALE - ¾"=1'-0"

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200 PATTON HALL
BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT: Self-Loosening of Anchor Nuts

SHEET NOTES:

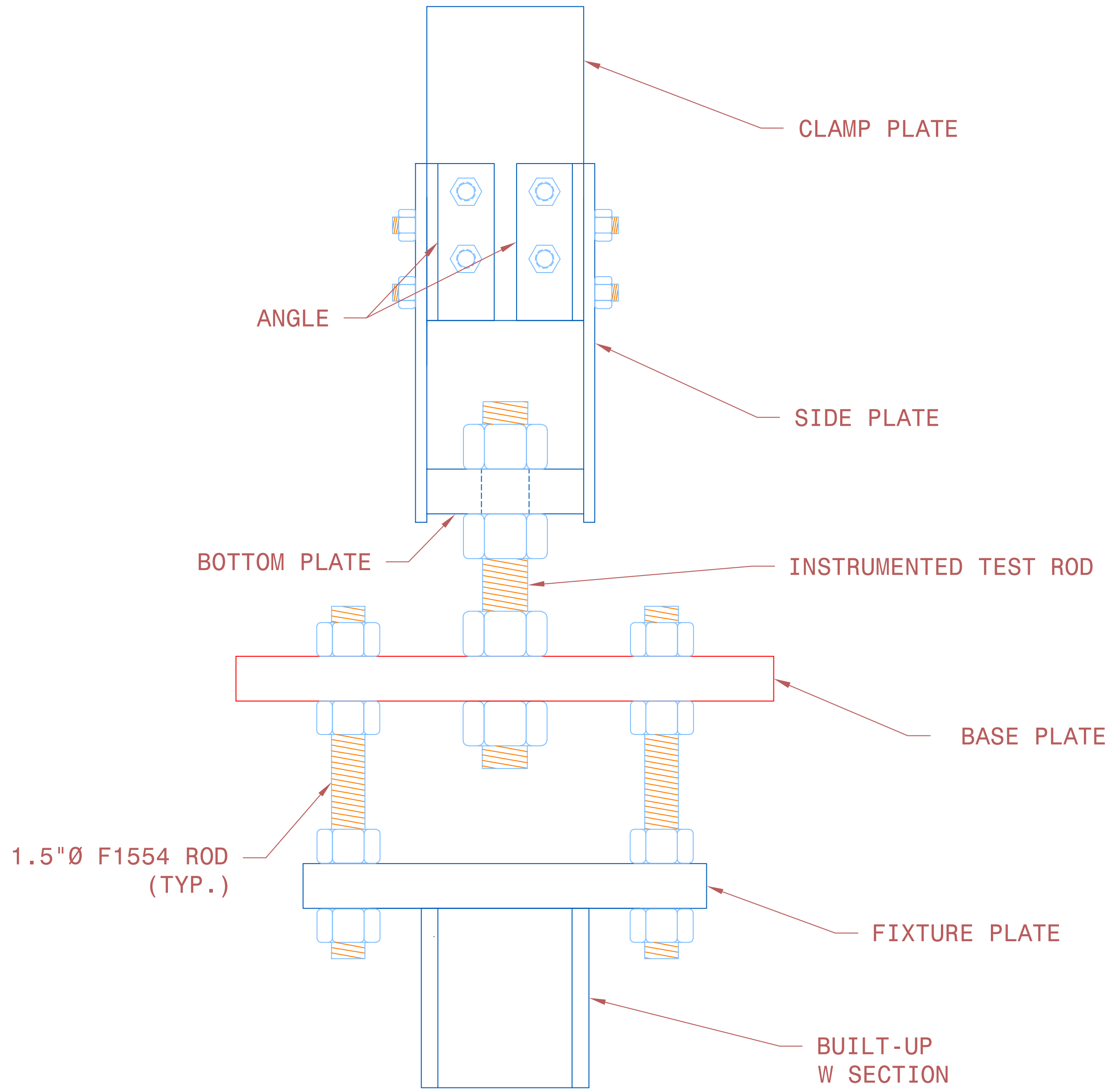
REVISIONS:

NO.	DATE	BY

DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 05/22/2018
PROJECT NO.: Number

SHEET TITLE: Large-Scale Testing of Steel Traffic Signals

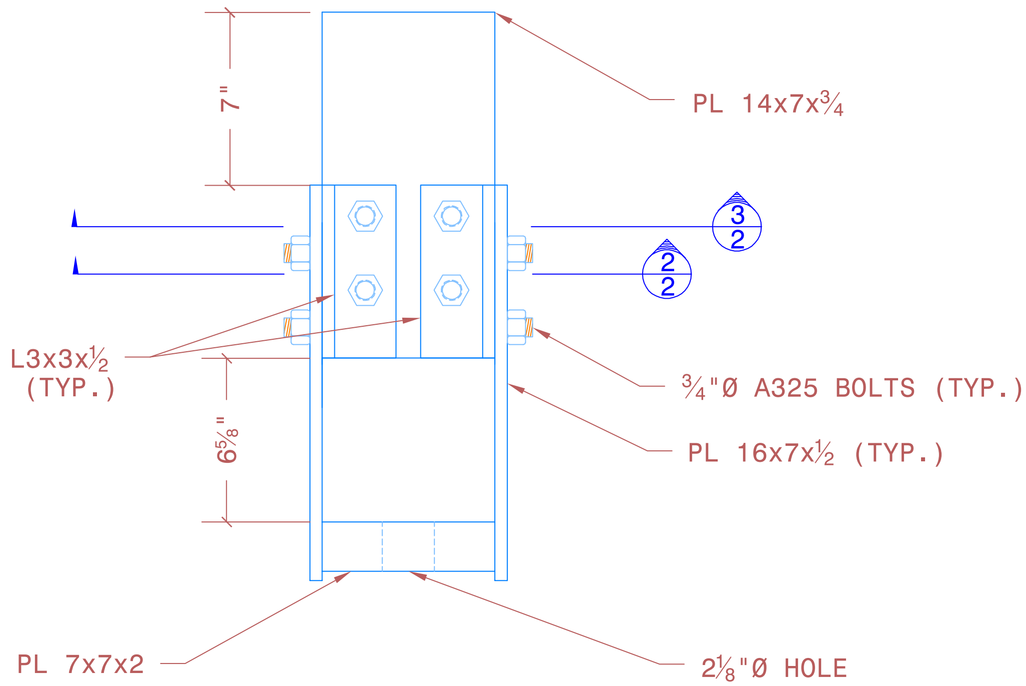
SHEET NO.: 4 of 4



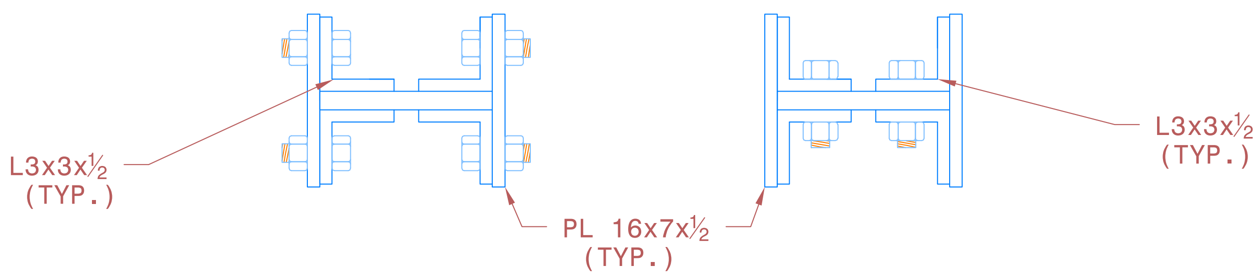
1 FULL ASSEMBLY
1 ELEVATION VIEW

SCALE - 1½"=1'-0"

Virginia Tech VIRGINIA TECH CHARLES E. VIA JR. DEPARTMENT OF CIVIL & ENVIRONMENTAL ENGINEERING 200 PATTON HALL BLACKSBURG, VA 24061 P: 540-231-6635	PROJECT: Self-Loosening of Anchor Nuts SHEET NOTES:	REVISIONS: NO. DATE BY DESIGNED BY: JSS DRAWN BY: JSS CHECKED BY: MHH DATE: 02/04/2019 PROJECT NO.: Number	SHEET TITLE: Small-Scale Testing SHEET NO.: 1 of 10



1 / 2 BOLT RIG
ELEVATION VIEW



2 / 2 BOLT RIG
PLAN VIEW

3 / 2 BOLT RIG
PLAN VIEW

SCALE - 1½"=1'-0"

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P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

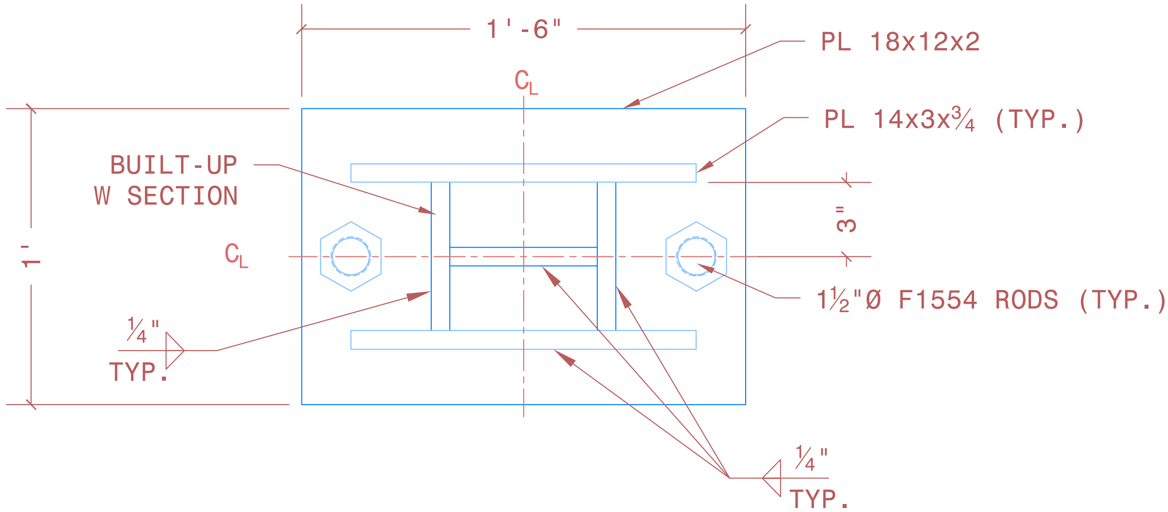
REVISIONS:

NO.	DATE	BY

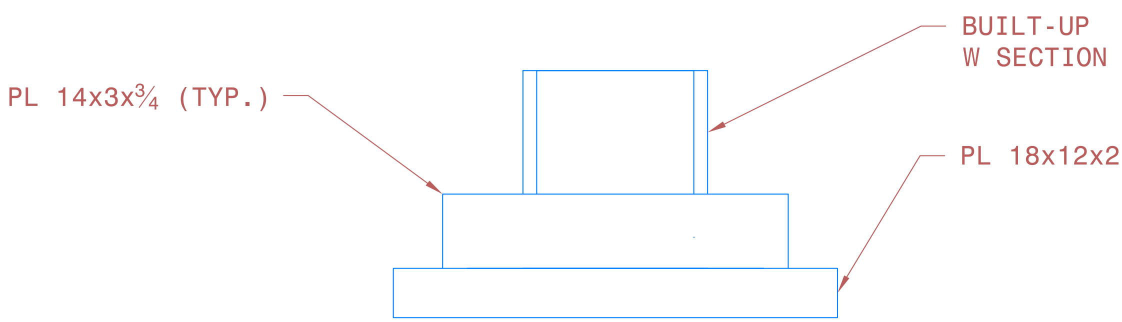
DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	02/04/2019
PROJECT NO.:	Number

SHEET TITLE:
Small-Scale Testing

SHEET NO.: 2 of 10



1 / 3 PLATE FIXTURE PLAN VIEW



2 / 3 PLATE FIXTURE ELEVATION VIEW

NOTE- REFER SHEET 5 FOR WELDS ON BUILT-UP W SECTION

SCALE - 1½"=1'-0"

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PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

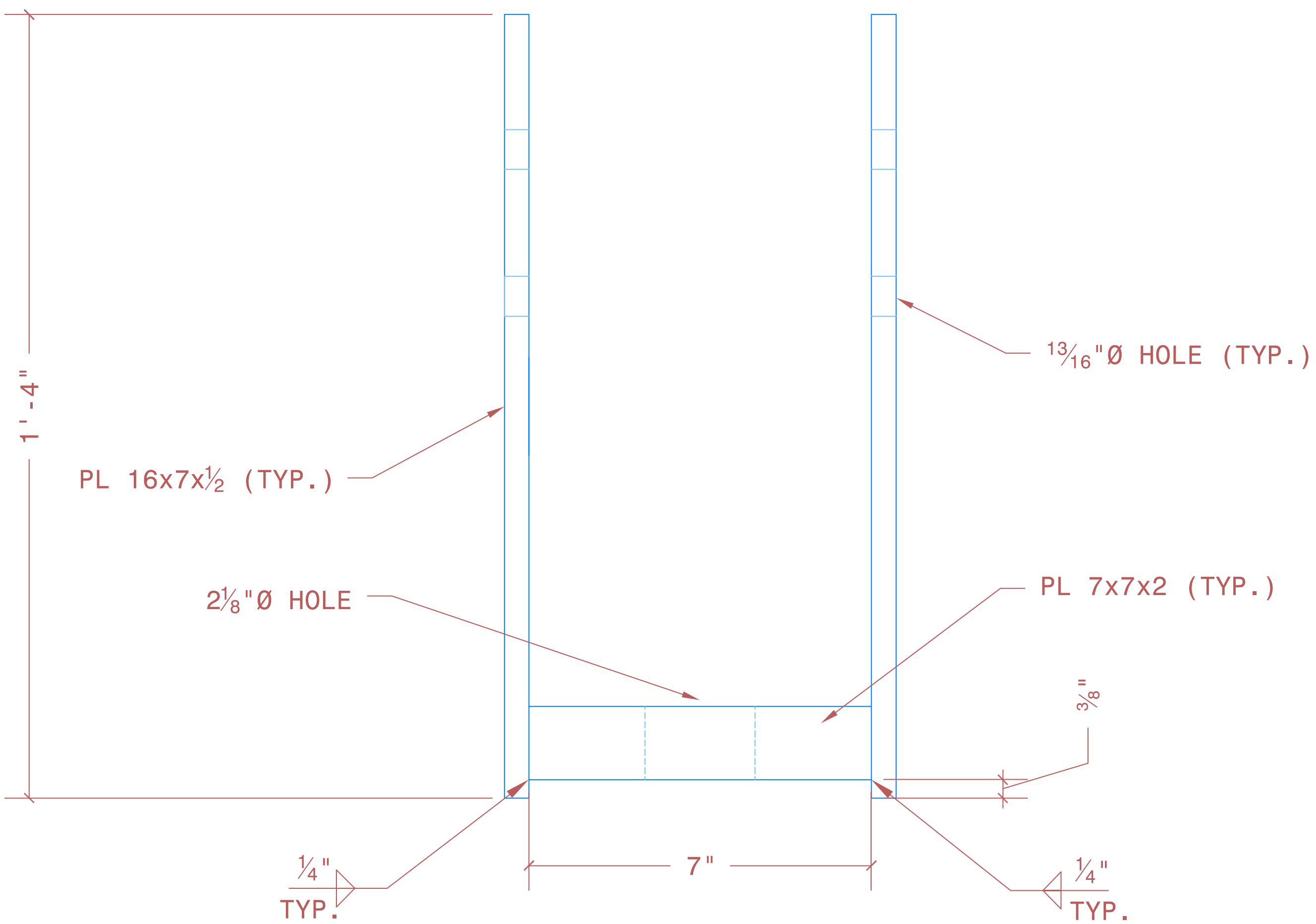
REVISIONS:

NO.	DATE	BY

DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 02/04/2019
PROJECT NO.: Number

SHEET TITLE:
Small-Scale Testing

SHEET NO.: 3 of 10



1 / 4 BOLT RIG ELEVATION VIEW

SCALE - 3"=1'-0"

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PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

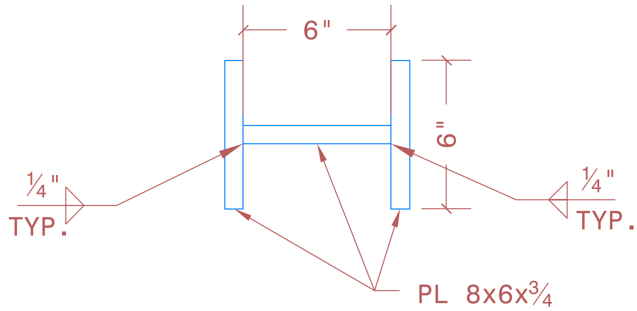
REVISIONS:

NO.	DATE	BY

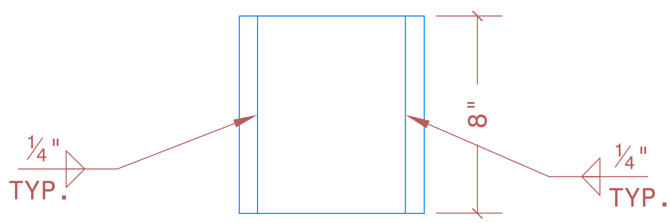
DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	02/04/2019
PROJECT NO.:	Number

SHEET TITLE:
Small-Scale Testing

SHEET NO.: 4 of 10



1 / 5 BUILT-UP W SECTION ELEVATION VIEW



2 / 5 BUILT-UP W SECTION PLAN VIEW

SCALE - 3"=1'-0"

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PROJECT: Self-Loosening of Anchor Nuts

SHEET NOTES:

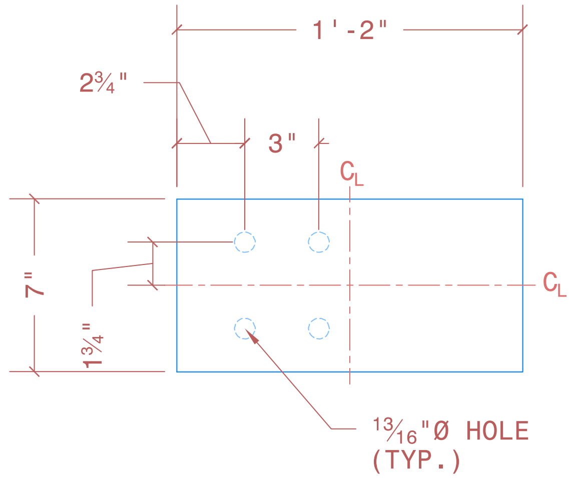
REVISIONS:

NO.	DATE	BY

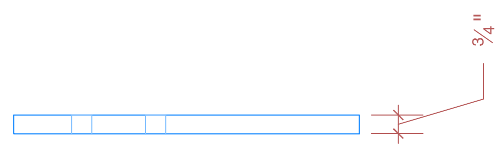
DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	02/04/2019
PROJECT NO.:	Number

SHEET TITLE: Small-Scale Testing

SHEET NO.: 5 of 10



1 / 6 CLAMP PLATE
PLAN VIEW



2 / 6 CLAMP PLATE
ELEVATION VIEW

SCALE - 1½"=1'-0"

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P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

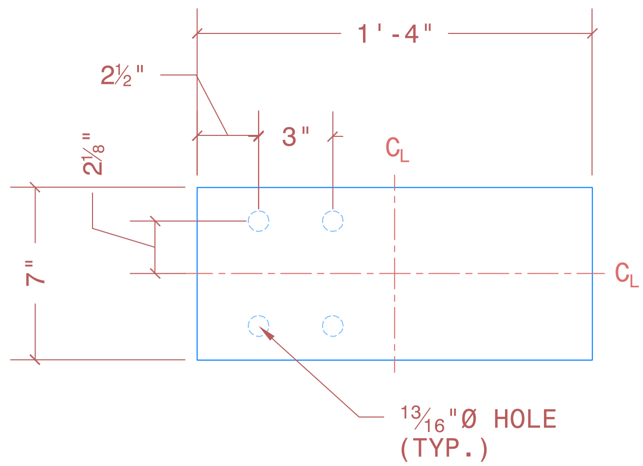
REVISIONS:

NO.	DATE	BY

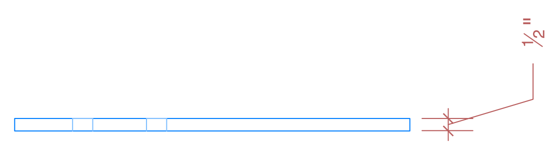
DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 02/04/2019
PROJECT NO.: Number

SHEET TITLE:
Small-Scale Testing

SHEET NO.: 6 of 10



1 / 7 SIDE PLATES
PLAN VIEW



2 / 7 SIDE PLATES
ELEVATION VIEW

SCALE - 1½"=1'-0"

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P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

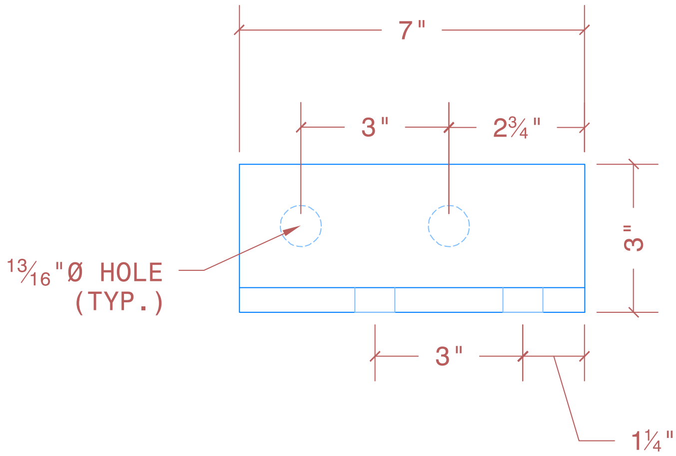
REVISIONS:

NO.	DATE	BY

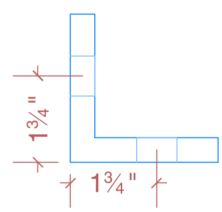
DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	02/04/2019
PROJECT NO.:	Number

SHEET TITLE:
Small-Scale Testing

SHEET NO.: 7 of 10



1 / 8 ANGLES
PLAN VIEW



2 / 8 ANGLES
ELEVATION VIEW

SCALE - 3"=1'-0"

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ENGINEERING
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BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

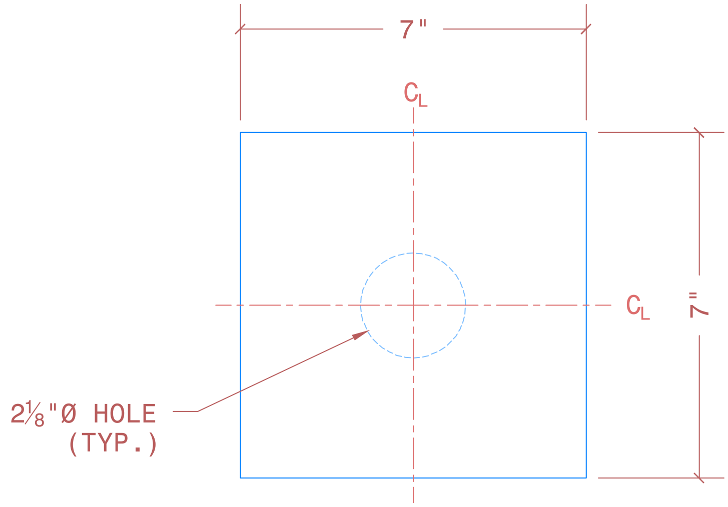
REVISIONS:

NO.	DATE	BY

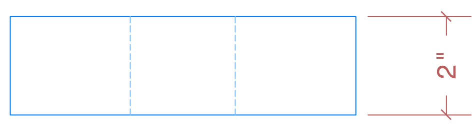
DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	02/04/2019
PROJECT NO.:	Number

SHEET TITLE:
Small-Scale Testing

SHEET NO.: 8 of 10



1 / 9 BOTTOM PLATE PLAN VIEW



2 / 9 BOTTOM PLATE ELEVATION VIEW

SCALE - 3"=1'-0"

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BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT: Self-Loosening of Anchor Nuts

SHEET NOTES:

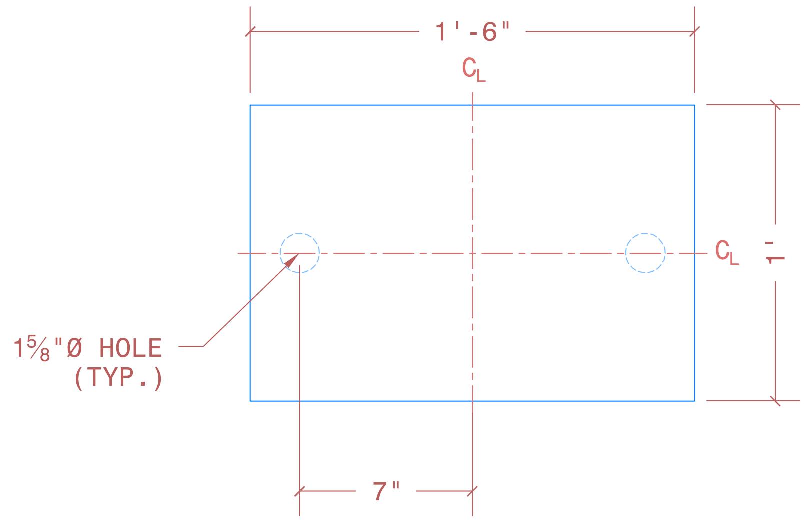
REVISIONS:

NO.	DATE	BY

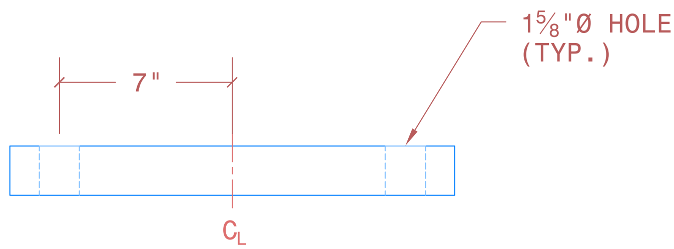
DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 02/04/2019
PROJECT NO.: Number

SHEET TITLE: Small-Scale Testing

SHEET NO.: 9 of 10



1 / 10 FIXTURE PLATE
PLAN VIEW



2 / 10 FIXTURE PLATE
ELEVATION VIEW

SCALE - 1½"=1'-0"

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BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

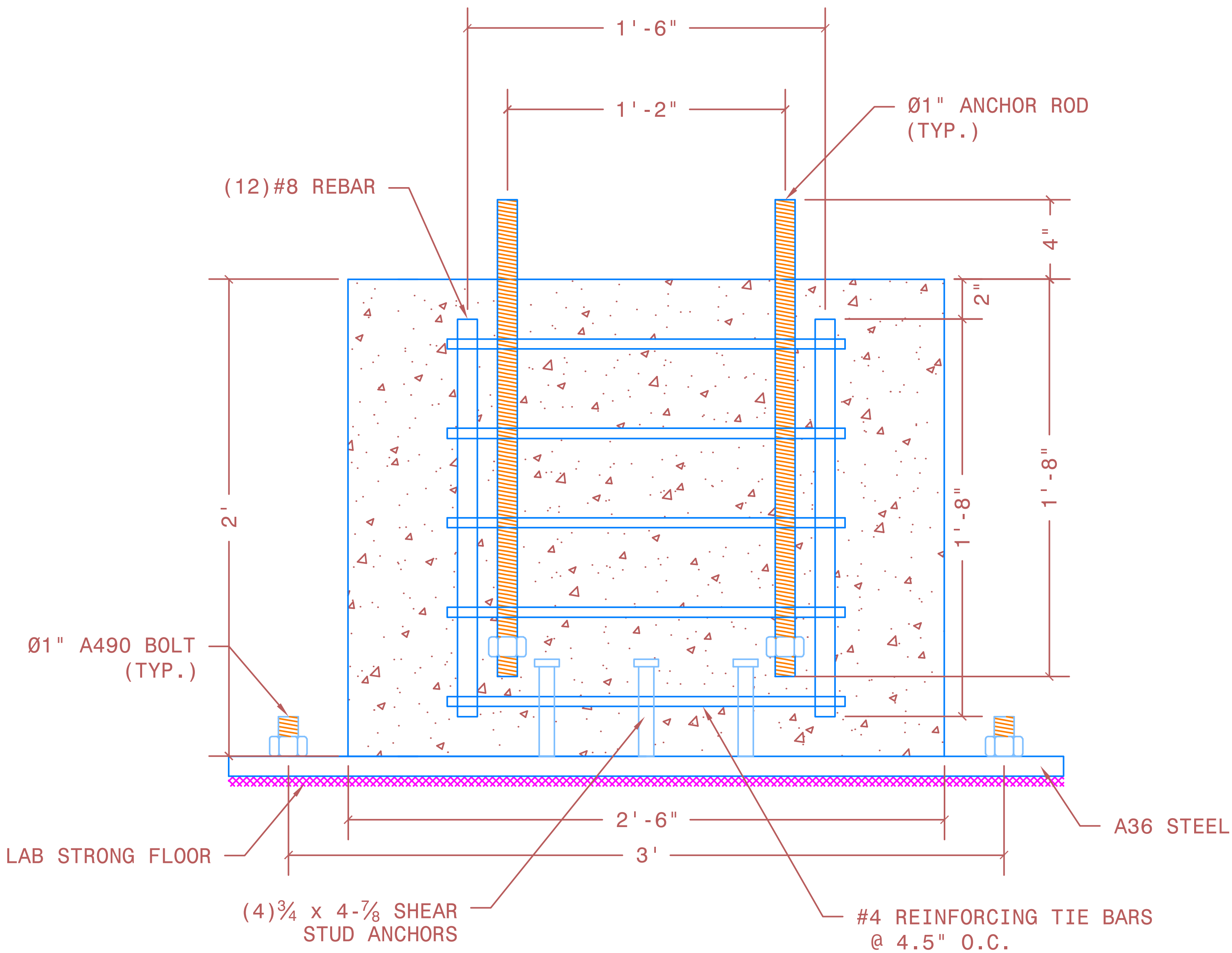
REVISIONS:

NO.	DATE	BY

DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	02/04/2019
PROJECT NO.:	Number

SHEET TITLE:
Small-Scale Testing

SHEET NO.: 10 of 10



ELEVATION VIEW
(1'-½"=1'-0")

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BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

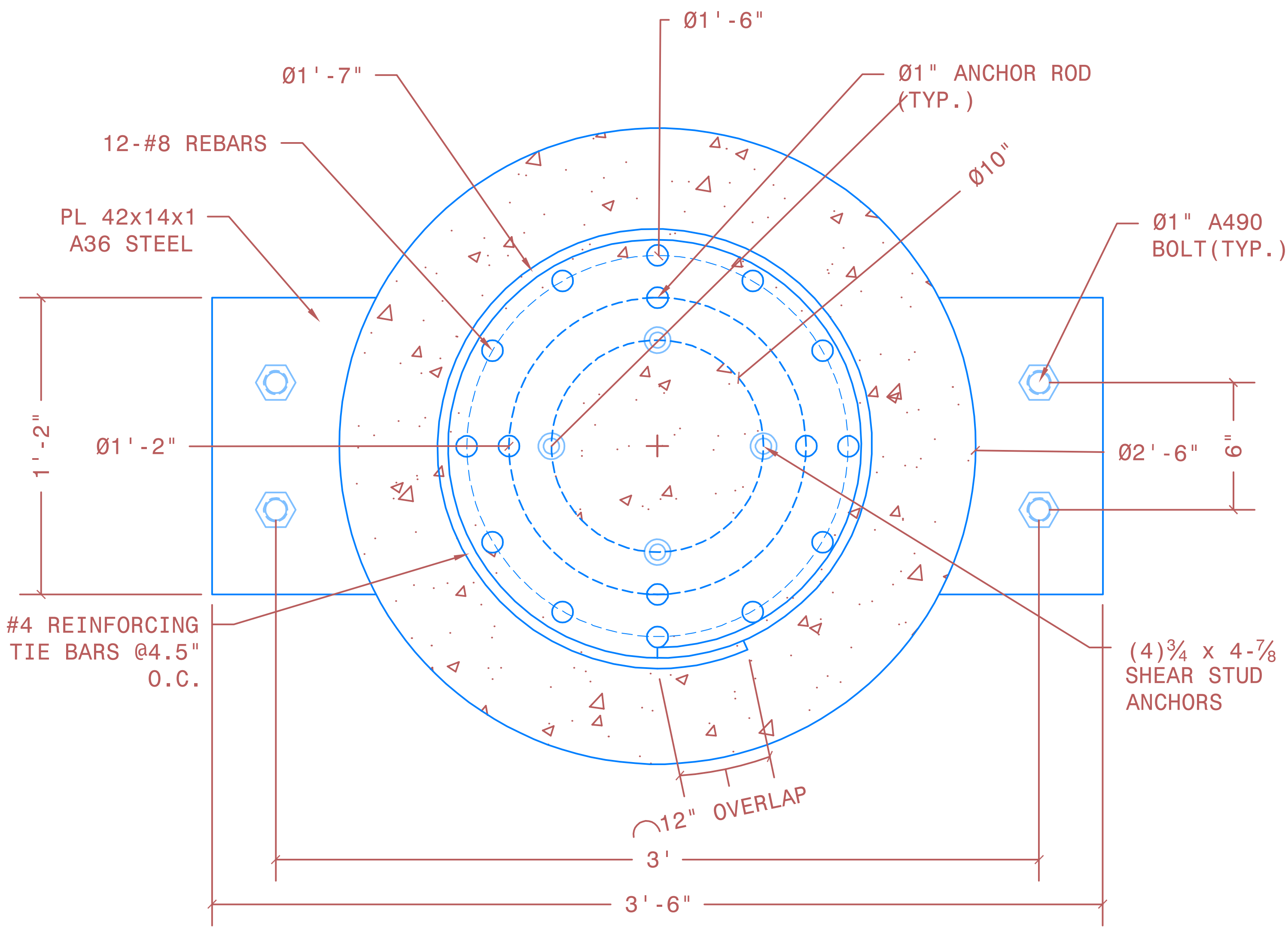
REVISIONS:

NO.	DATE	BY

DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	07/09/2019
PROJECT NO.:	Number

SHEET TITLE:
T-Base Foundation

SHEET NO.: 1 of 2



PLAN VIEW
(1-½"=1'-0")

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200 PATTON HALL
BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

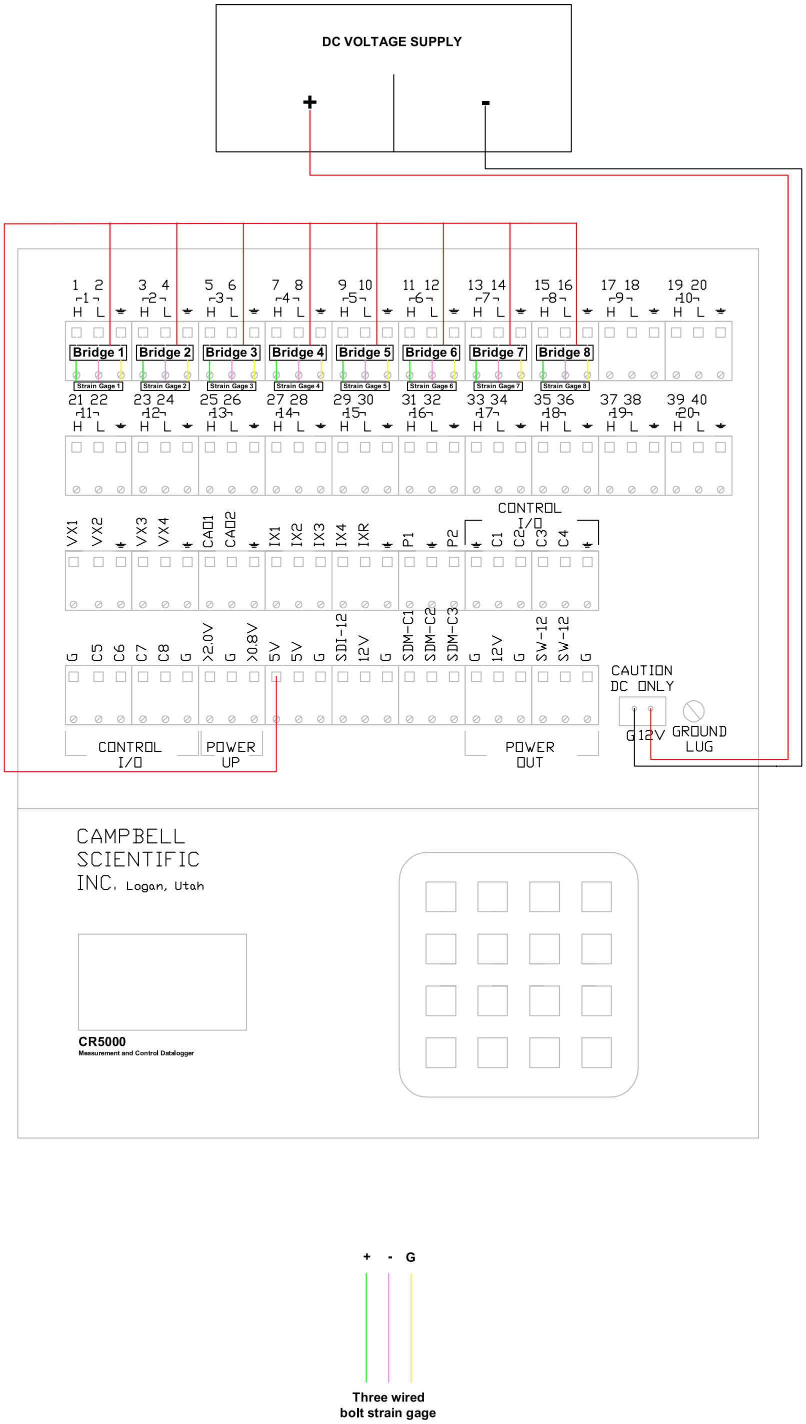
REVISIONS:

NO.	DATE	BY

DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 07/09/2019
PROJECT NO.: Number

SHEET TITLE:
T-Base Foundation

SHEET NO.: 2 of 2



1 DAQ WIRING

1 PLAN VIEW

SCALE - 4½"=1'-0"

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BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT:

Self-Loosening of Anchor Nuts

SHEET NOTES:

REVISIONS:

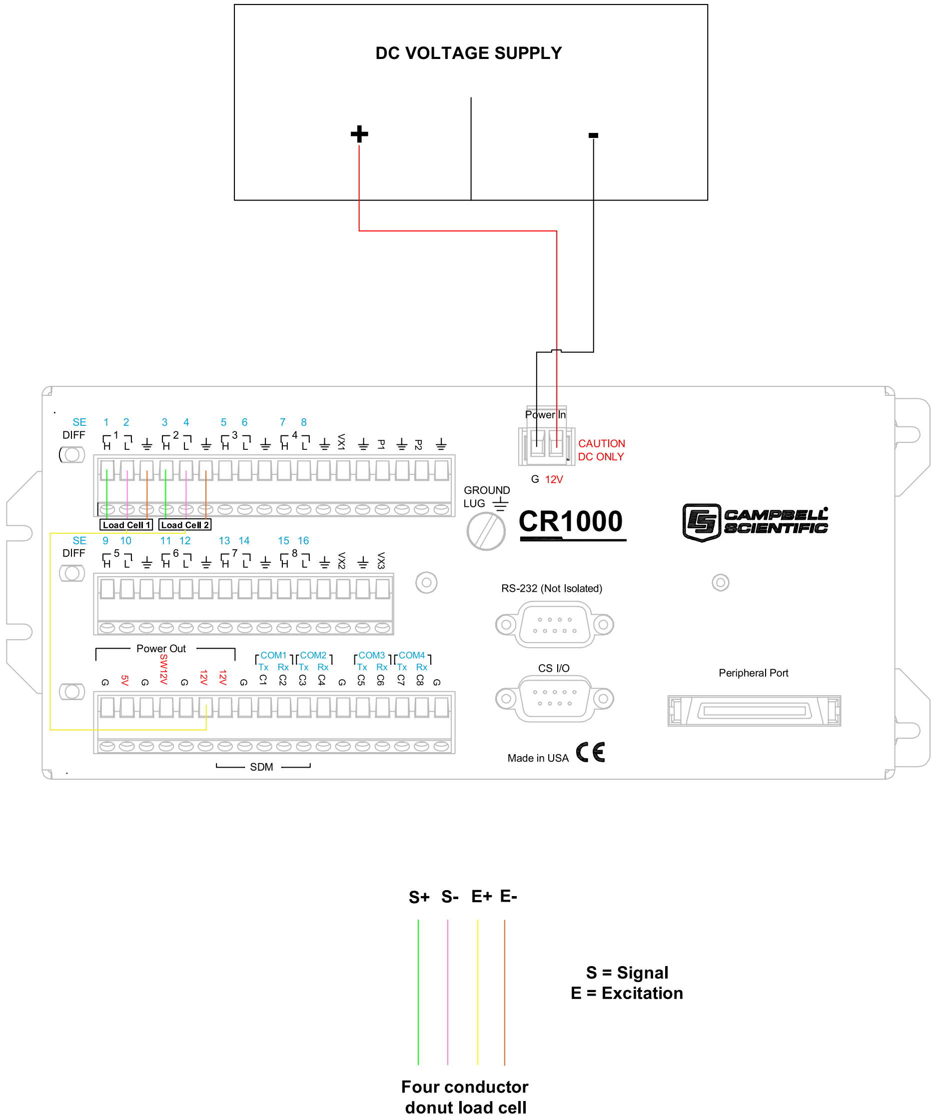
NO.	DATE	BY

DESIGNED BY:	JSS
DRAWN BY:	JSS
CHECKED BY:	MHH
DATE:	03/18/2020
PROJECT NO.:	Number

SHEET TITLE:

DAQ Wiring (Tightening Procedures - Double Nut Connections and Snug-tight Study)

SHEET NO.: 1 of 5



1 DAQ WIRING
2 PLAN VIEW

SCALE - 6"=1'-0"

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BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

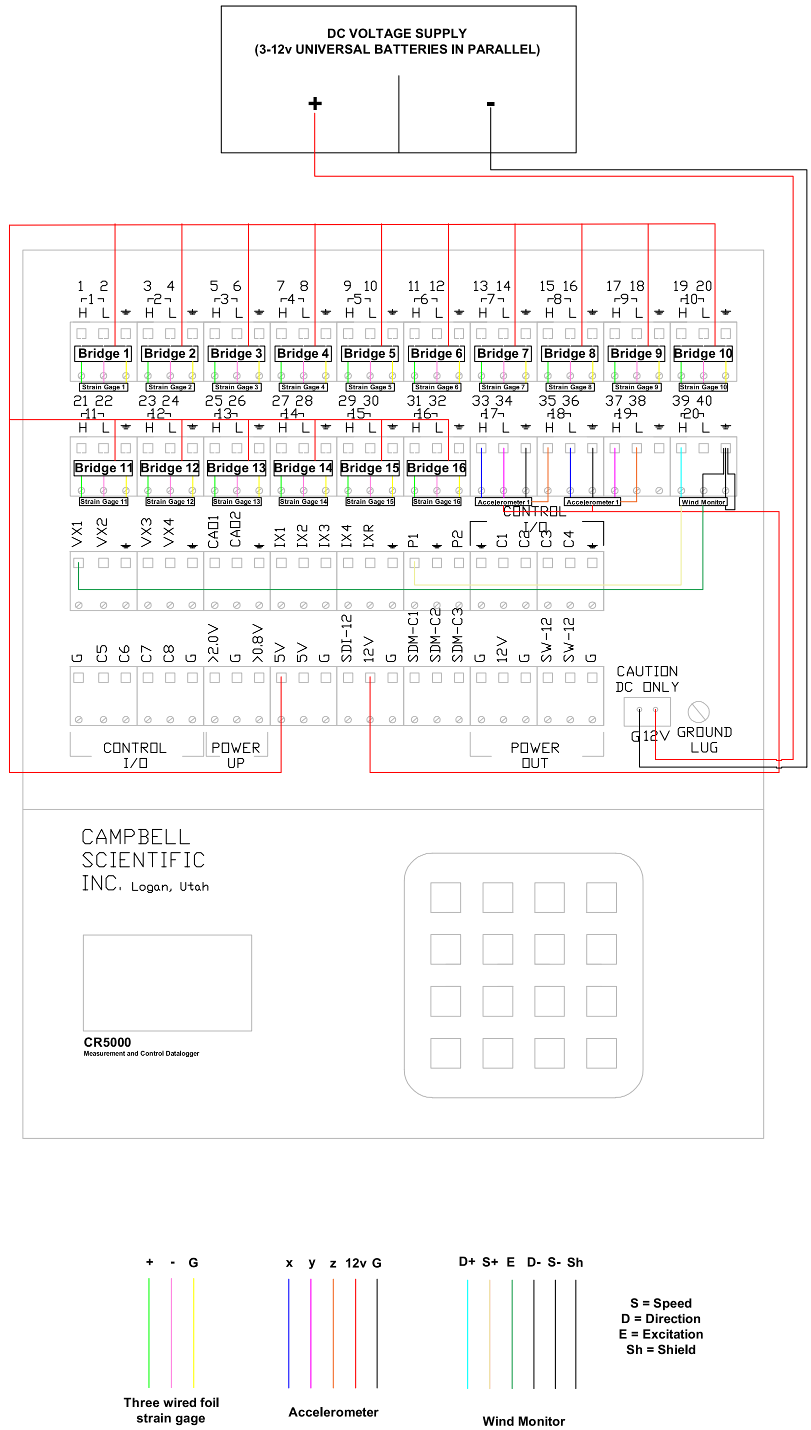
REVISIONS:

NO.	DATE	BY

DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 03/18/2020
PROJECT NO.: Number

SHEET TITLE:
DAQ Wiring (Tightening Procedures - Single Nut Connections)

SHEET NO.: 2 of 5



1 DAQ WIRING
3 PLAN VIEW

SCALE - 4½"=1'-0"

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P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

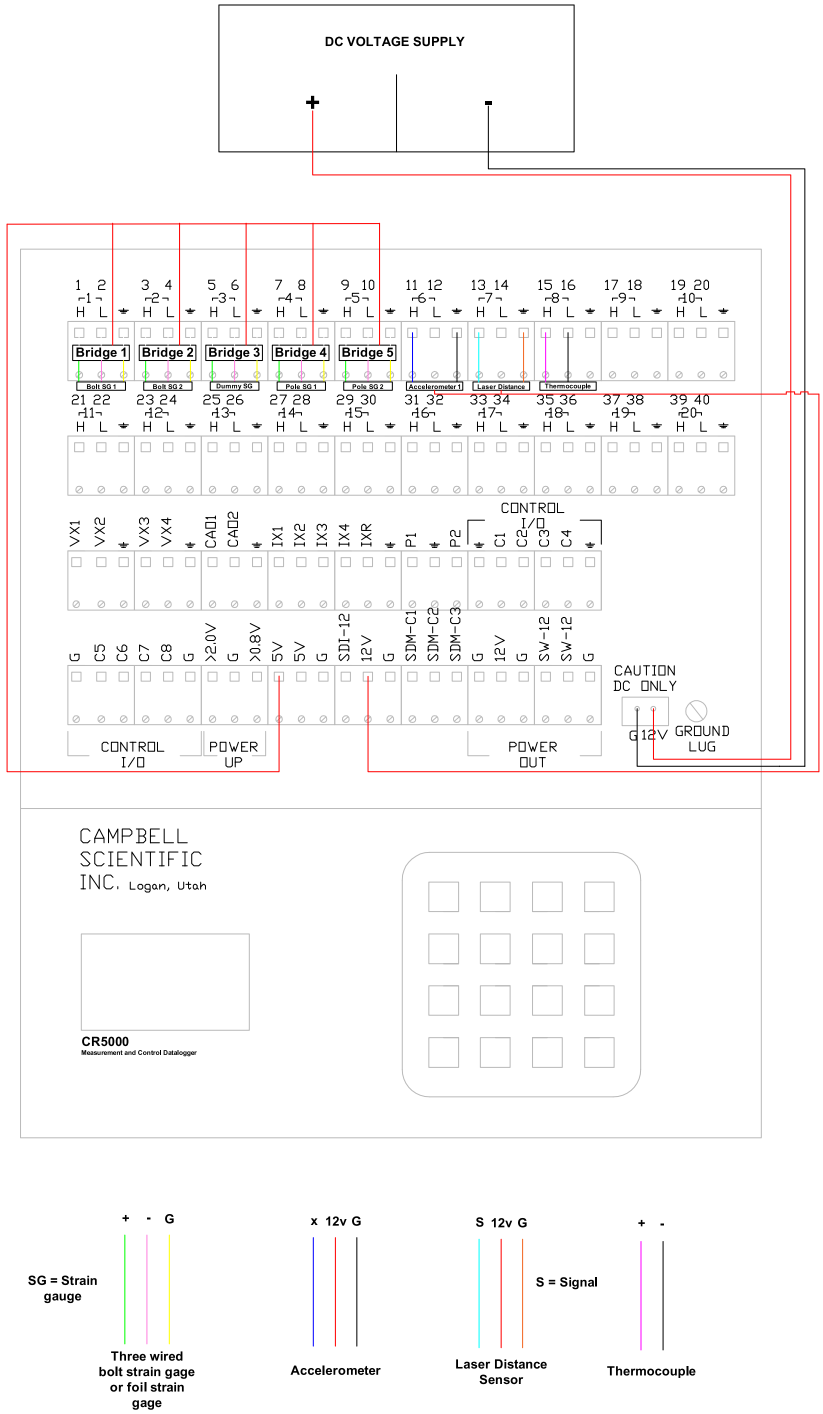
REVISIONS:

NO.	DATE	BY

DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 03/18/2020
PROJECT NO.: Number

SHEET TITLE:
DAQ Wiring (Field Monitoring)

SHEET NO.: 3 of 5



1 / 4 DAQ WIRING PLAN VIEW

SCALE - 4½"=1'-0"

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P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

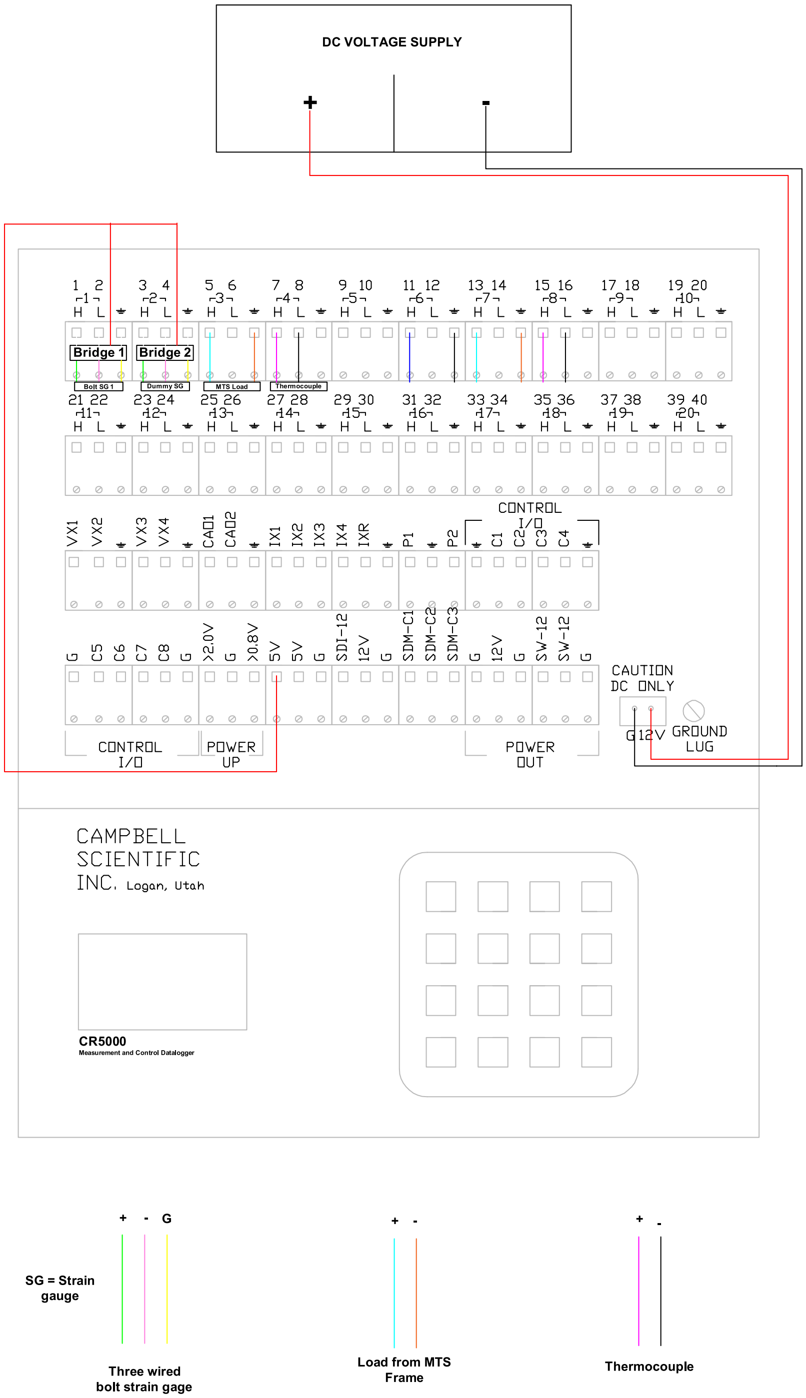
REVISIONS:

NO.	DATE	BY

DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 03/18/2020
PROJECT NO.: Number

SHEET TITLE:
DAQ Wiring (Large-scale Testing)

SHEET NO.: 4 of 5



1 / 5 DAQ WIRING PLAN VIEW

SCALE - 4½"=1'-0"

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BLACKSBURG, VA 24061
P: 540-231-6635

PROJECT:
Self-Loosening of Anchor Nuts

SHEET NOTES:

REVISIONS:

NO.	DATE	BY

DESIGNED BY: JSS
DRAWN BY: JSS
CHECKED BY: MHH
DATE: 03/18/2020
PROJECT NO.: Number

SHEET TITLE:
DAQ Wiring (Small-scale Testing)

SHEET NO.: 5 of 5