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Methods to Ensure Appropriate Installation and Prevent Loosening of Anchor Nuts on Ancillary Highway Structures

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The study found that the current Virginia Department of Transportation tightening procedures for double-nut moment connections contain some discrepancies, which can lead to under- or over-tightening of anchor rods. Recommendations were provided for properly tightening grade 36 and 55 anchor rods. The study also showed that the current manufacturer recommended tightening torque for single nut connections on T-bases are inadequate to prevent loosening. Recommendations were made for specifying deep sockets, long extensions, and proper lubrication to facilitate tightening these connections. Snug tight testing showed that the snug tight condition is highly variable. Recommendations were provided for using an appropriate wrench length depending on the diameter of the anchor rod being tightened. The recommendations provided in this study will aid in preventing anchor nut loosening, which will make for safer ancillary structures requiring less maintenance.

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FINAL REPORT

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ABSTRACT

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INTRODUCTION

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 towers. 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 some cases, the top nut on these double nut connections is a jam nut, which is typically half the thickness of a standard nut, used to prevent loosening during vibrations. In the past, there have been incidents where ancillary structures have failed, resulting in the structure falling onto highways. 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 these loose nuts 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 were found to have loose anchor nuts.

Anchor nuts, if loose, can 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 Federal Highway Administration (FHWA) guidelines (Garlich and Thorkildsen 2005), American Association of State Highway and Transportation Officials (AASHTO) specifications (AASHTO 2015), and Virginia Department of Transportation (VDOT) implementation documents (VDOT 2016a), are followed for fastening anchor nuts onto the anchor rods of ancillary structures. The tightening specifications first require that the top and bottom anchor nuts are made snug-tight, 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, two areas are lacking from 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. Second, VDOT has tightening procedures for typical strength anchor rods, made from either grade 36 or 50 ksi, but does not have tightening procedures for high strength anchor rods, made from grade 105 ksi, even though 105 ksi strength rods are referred to within the AASHTO specifications (AASHTO 2015) and FHWA guidelines (Garlich and Thorkildsen 2005). VDOT does not have tightening procedures for 105 ksi strength rods because of an agency preference to have a larger quantity of lower typical strength rods in a connection rather than a smaller quantity of high strength rods for redundancy. No matter the strength of the anchor rod used, an improperly tightened connection 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 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). The loosening is typically divided into two stages (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 thread roots. The second stage starts when the preload has reached a threshold value resulting in a rapid decrease in preload and the nut rotating or backing off. These studies have also shown that loss in pretension is a function of the number of vibratory cycles (Goodier and Sweeney, 1945; Jiang et al., 2003, 2004; Junker, 1969; Yamamoto and Kasei, 1984).

Galvanization and overtapping of threads also pose another concern. Overtapping is the process of making the nut threads larger to accommodate the dimensional increase in the rod threads after galvanization. Anchor rods and nuts can be galvanized to increase their service life by preventing corrosion. 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 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.

Several 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 had some discrepancies or did not cover an entire spectrum of diameter/grade of anchor rods. Some of these studies and discrepancies are discussed in the following sections. There has been minimal previous research done 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 are not well understood and require further research.

PURPOSE AND SCOPE

The purpose of this research was two-fold. The primary purpose of the research was to investigate the potential causes of loosening of anchor nuts on ancillary structures and recommend any remedial measures to prevent this loosening. The second purpose of the research was to review the current tightening procedures for single-nut and double-nut connections in ancillary structures and recommend any changes, should any discrepancies be found.

The scope of this research included laboratory and field components. The laboratory testing was performed in the Thomas Murray Structures Laboratory at Virginia Tech. Tightening studies on double-nut moment connections and single-nut connections (such as transformer base poles) were performed in the laboratory. Field monitoring of two ancillary structures was conducted for a period of four months in Carrollton, Virginia. Large-scale and small-scale vibration testing was performed on ancillary structures in the laboratory to study the effect of wind-induced vibrations. Thread fabrication tolerance evaluation was also performed on anchor rods and nuts procured from different suppliers to study the effect of galvanization and overtapping on loosening of anchor nuts. The thread tolerance study was performed using a digital microscope and Vernier calipers in the laboratory.

Out-of-service traffic signals were procured from the VDOT Lynchburg District for large-scale testing. The VDOT Hampton Roads District also provided assistance in the form of a bucket truck and crew during instrumentation of the field monitoring task.

METHODS

The methods in this study included the following tasks:

1. A literature review was conducted.
2. Tightening procedures for double nut moment connections on ancillary structures were evaluated.
3. Field monitoring was conducted on two in-service ancillary structures.
4. Large-scale vibration testing was conducted to evaluate the effect of wind-induced vibrations.
5. Small-scale vibration testing was conducted to validate the results from large-scale testing.
6. An evaluation of thread fabrication tolerance was conducted to investigate the effect of galvanization and overtapping on threads.
7. Tightening procedures for anchor nuts on transformer base (T-base) poles were investigated.
8. An evaluation of inspection methods was conducted.
9. A snug-tight study was conducted to investigate the effect of wrench lengths and personnel strength on snug-tight pretension.
10. A development of nut tightening procedures was completed.

Task 1: Literature Review

A thorough literature review was undertaken to obtain information from past research studies, various specifications, and guidelines regarding important topics such as the current tightening procedures for anchor rod connections (single-nut and double-nut), anchor rod loosening, vibration and fatigue testing of ancillary structures, thread tolerance related issues, and variation of snug-tight pretension. A summary of the conducted literature review has been provided in the results section.

Task 2: Tightening Procedures for Double Nut Moment Connections on Ancillary Structures

Specimen Matrix

The turn-of-the-nut tightening procedure was used to tighten three grades of ASTM F1554 anchor rods: 36, 55, and 105 (ASTM, 2015a). The relationship between the applied torque, pretension, and nut rotation was evaluated. Five anchor rod diameters (0.75 in, 1 in, 1.25 in, 1.5 in, and 2 in) were tested. The anchor rods were tightened onto six different base plates, three made of A36 steel (ASTM, 2014a) and three made of 6061 T-6 aluminum (ASTM, 2014b), representative of common industry practice. The base plates were 24 in x 12 in, and 100 anchor rods were fastened onto steel and aluminum base plates in a double-nut moment connection. All three grades of a particular diameter of anchor rods were tightened on a base plate with the thickness equal to the diameter of the anchor rod to reflect the common industry practice. It is also recommended that base plate thickness be at least equal to diameter of the anchor rod to prevent any prying action (Kaczinski et al., 1998). The specimen matrix for the tightening study is shown in Table 1.

Table 1. Specimen matrix for tightening procedures of anchor rods in double-nut moment connections

Anchor Rod			Base Plate (24 in x 12 in)		Anchor Nuts	
Diameter (in)	Grade	Quantity	Grade	Thickness (in)	Grade	Style
1	36	8	A36 Steel	1	A563 Grade A	Hex
1½		6		1½	A563 Grade A	Hex
2		5		2	A563 Grade A	Heavy Hex
1	55	6		1	A194 Grade 2H	Heavy Hex
1½		5		1½	A194 Grade 2H	Heavy Hex
2		5		2	A194 Grade 2H	Heavy Hex
1	105	6		1	A194 Grade 2H	Heavy Hex
1½		4		1½	A194 Grade 2H	Heavy Hex
2		4		2	A194 Grade 2H	Heavy Hex
¾	36	6	6061-T6 Aluminum	¾	A563 Grade A	Hex
1		6		1	A563 Grade A	Hex
1¼		5		1¼	A563 Grade A	Hex
¾	55	5		¾	A194 Grade 2H	Heavy Hex
1		6		1	A194 Grade 2H	Heavy Hex
1¼		5		1¼	A194 Grade 2H	Heavy Hex
¾	105	7		¾	A194 Grade 2H	Heavy Hex
1		6		1	A194 Grade 2H	Heavy Hex
1¼		5		1¼	A194 Grade 2H	Heavy Hex

Single nut connections are recommended to be tightened to the same amount of pretension as the double-nut moment connections as per the NCHRP report 469 (Dexter and Ricker, 2002). Single-nut connections are commonly found on A356-T6 grade cast aluminum bases (F_y = 35 ksi) in aluminum poles (ASTM, 2018a). Due to material availability of cast aluminum in base plates, a similar yield strength material 6061 T-6 (F_y = 26 ksi) was used instead for the aluminum base plates (ASTM, 2014b).

All of the anchor rods, nuts, and washers were galvanized to align with specification requirements. The rods and nuts had Unified Coarse Pitch (UNC) threads. ASTM A194 grade nuts are allowed within the specification as a substitute for ASTM A563 grade nuts and, therefore, both grades were used throughout testing depending on their availability in the market (ASTM, 2015b; ASTM, 2016). Two nut styles (heavy hex and hex) and three anchor nut grades (A, DH, and 2H) were used depending on the diameter of anchor rod as per the guidelines in ASTM F1554 (ASTM, 2015a) (see Table 1). Standard ASTM F436 round washers were used with rods and nuts for tightening (ASTM, 2018b).

Instrumentation and Test Setup

Each base plate specimen was fabricated with a hole in the center of the plate for the anchor rod specimens to pass through. All six base plates were instrumented with eight bolt strain gages equally spaced around the anchor rod hole (see Figure 1). The base plates were instrumented, instead of the rods, to reduce time and cost involved with instrumentation of every anchor rod tested. The strain gages were placed into 0.078 in predrilled holes located below the centroid of the washer area. The strain gages were instrumented such that the gage center was at mid-thickness of the base plate. This was done to effectively measure the maximum compressive strains in the base plate during tightening.

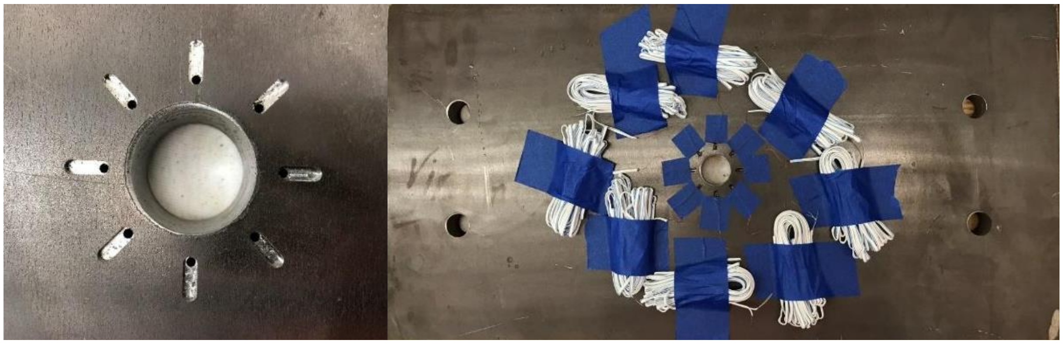


Figure 1. Drilled strain gage holes (left) and base plate with instrumented eight bolt strain gages (right)

Base plates were fastened to the top flanges of two I-shaped beam stubs (W27x217) using 0.875 in diameter ASTM A490 bolts, as shown in Figure 2. Three calibrated manual torque wrenches with capacities of 300 ft-lbs, 600 ft-lbs, and 1500 ft-lbs were used for tightening the anchor rods. Two torque multipliers with an output capacity of 2000 ft-lbs and 8000 ft-lbs and multiplication ratios of 3.6:1 and 4.6:1, respectively, were used for increasing the output torque. The torque multiplier was allowed to react against a 6 in x 6 in x ¾ in steel angle. A 360˚ circular gauge with 1˚ markings around the anchor rod hole was used for measuring nut rotations.

Figure 2. Test-setup for tightening anchor rods

A data logger was used for measuring strains in the bolt strain gages during testing. A 300-kip capacity load frame was used to calibrate the instrumented base plates prior to anchor rod tightening. The base plates were loaded in compression using washers at the top and bottom to simulate boundary conditions during tightening. A strain-vs-force calibration curve was made for each individual base plate and each calibration curve was found to be linear with a coefficient of determination (r-squared) greater than or equal to 0.99. The calibration was verified against finite element (FE) models. The plates were modeled in Abaqus 6.14 using 8-noded linear brick elements with reduced integration and hourglass control (C3D8R). A global seed size of 0.25 in was chosen along with creation of 40 local nodes at the anchor rod hole for mesh refinement (see Figure 3). The average percentage difference between the calibration results and FE results was found to be less than 10%. Since tension in the anchor rod must be equal to the compression in the plate during tightening, the calibration curve was further used to calculate the effective tensile stress in the anchor rod. This was done by dividing the calculated force applied on the plate during tightening by the tensile stress area of the rod.

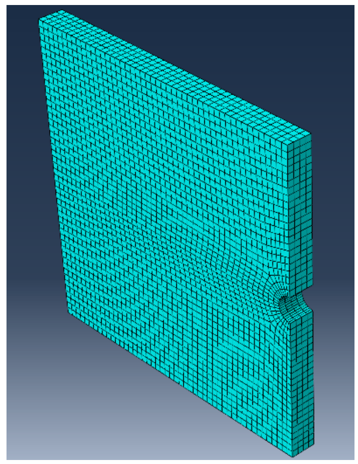


Figure 3. Mesh at the anchor rod hole for the half symmetric finite element model of 1 in plate

Tightening Procedure

The following step-by step tightening procedure, similar to the one specified in the AASHTO, FHWA, and VDOT specification documents, was followed during the tightening of the anchor rod specimens (see Figure 4):

1. The threads of the anchor rod, threads of the nuts, and flat bearing surfaces were lubricated with beeswax.
2. Both nuts were run up the rod by hand to verify that they could be rotated with ease.
3. The base plate and the reaction angle were fastened to the I-stubs using 0.875 in diameter A490 bolts. The support stubs were further fastened to the floor of the laboratory.
4. The anchor rod to be tested was passed through the hole in the base plate. The connection was made hand-tight by running the nuts and the washers onto the rod until they were in contact with the base plate. At this position, the bottom nut was made snug-tight using a wrench (18 in to 24 in long).
5. An adjustable wrench was used to prevent the bottom nut from rotating during the tightening procedure. The wrench was clamped to the bottom side of the base plate.
6. A 360˚ radial gauge was fixed to the base plate around the rod hole for measuring nut rotations.
7. An 18 in to 24 in long wrench, depending on the diameter of the anchor rod and size of the nut, was also used for snug-tightening the top nut. The top nut was snug-tight such that the snug-tight pretension as recorded from the strain gages was in the range of 1-10 ksi.
8. A zero degree mark was made on the faces of the rod, top nut, and top washer.

9. A manual torque wrench and torque multiplier was used to turn the top nut beyond snug-tight condition.
10. Torque was applied incrementally, and the corresponding pretension in the anchor rods and change in nut rotation was recorded.

Figure 4. Anchor nut tightening performed on a 2 in anchor rod

Task 3: Field Monitoring

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 5). The structures were instrumented with accelerometers, a wind monitor, and strain gages. The sensor data history was collected 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 5. Instrumented luminaire and traffic signal near the east coast of Virginia

Tests Performed

Pluck tests were performed on the individual poles to quantify their dynamic characteristics (see Figure 6). Pluck tests were conducted by pulling the top of the poles laterally using an instrumented cable, and then the cable was released. 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 6. 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 the results section of 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 (6 mph, 10 mph, and 15 mph) as set during the long-term monitoring. The trigger level was initially set at 6 mph, but was then increased to 10 mph and 15 mph over the course of the field monitoring duration. The trigger levels were increased since wind speeds less than 10 mph contributed to only small vibrational stresses in the instrumented poles which were expected to have negligible effect on anchor nut loosening.

Instrumentation

A propeller-type anemometer 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 ft aluminum pipe, which was clamped to the top of the 25 ft light pole. Therefore, wind speeds and direction were measured at the height of approximately 33 ft above the ground, which is the standard height used for wind speed computations in ASCE and AASHTO specifications.

One tri-axial accelerometer 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.

Eight temperature compensated strain gages 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 2 ft above the base plate of the luminaire and 2 ft above the hand-hole of the traffic signal. This was done to avoid any stress risers due to sharp geometric discontinuities around the hand-hole. A K-type thermocouple 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 monitoring. All the instrumented sensors are shown in Figure 7.

Figure 7. Wind monitor (left), accelerometer (center), and strain gages (right)

A data logger 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 data acquisition system. The data logger was further connected to a cellular modem 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 8). The batteries were charged by a 7.5A – 12V smart battery charger for approximately 8 hours during each night when 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.

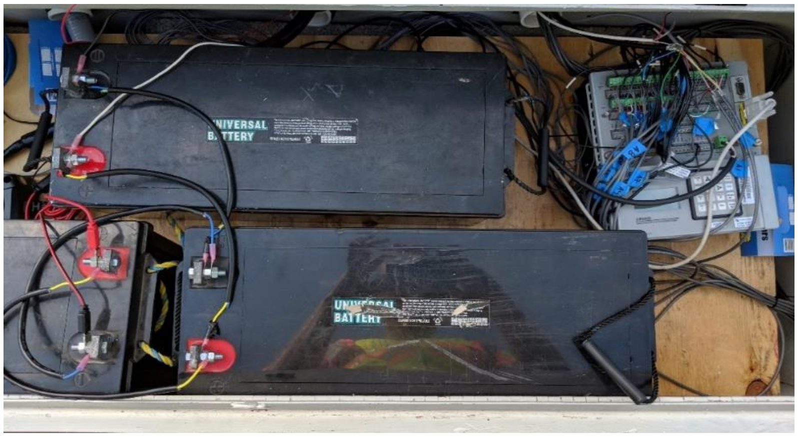


Figure 8. Parallel battery connection for charging datalogger

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. 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).

Task 4: Large-scale Vibration Testing

Large-scale testing involved vibration testing of one full-scale out-of-service 4-anchor rod configuration traffic signal in the Thomas M. Murray structures laboratory at Virginia Tech. The traffic signal was 20 ft in height with an outer diameter of 11 in at the bottom and 9 in at the top. The pole wall was 0.1875 in thick. The anchor rods were grade 55 and 1.25 in in diameter. The base plate was 1.5 in thick. The mast arm length was 32 ft with 0.1875 in wall thickness. The traffic signal was vibrated in resonance using a motor with an eccentric mass. Anchor rods were instrumented with bolt strain gages to measure pretension in the rod. Pretension and vibration stress range were varied to observe the relationship between the number of vibration cycles and pretension loss.

Test Setup

Typically, an ancillary structure is fastened to the anchor rods, which are embedded in a concrete foundation. However, a reaction box fixture was used instead of a concrete foundation in order to save time and effort involved in the process of pouring, casting, and curing of concrete (see Figure 9). This also ensured that multiple poles could be tested using the same reaction box fixture. The traffic signal pole was fastened to the anchor rods on the front side of the reaction box fixture using a double-nut moment connection. The same anchor rods were then fastened to the vertical plates of the fixture block. This was done to ensure that the connection simulated the same fixed boundary conditions as with a concrete foundation in the field. Cross stiffeners were welded on the inside of the fixture block to increase the stiffness of the fixture block.

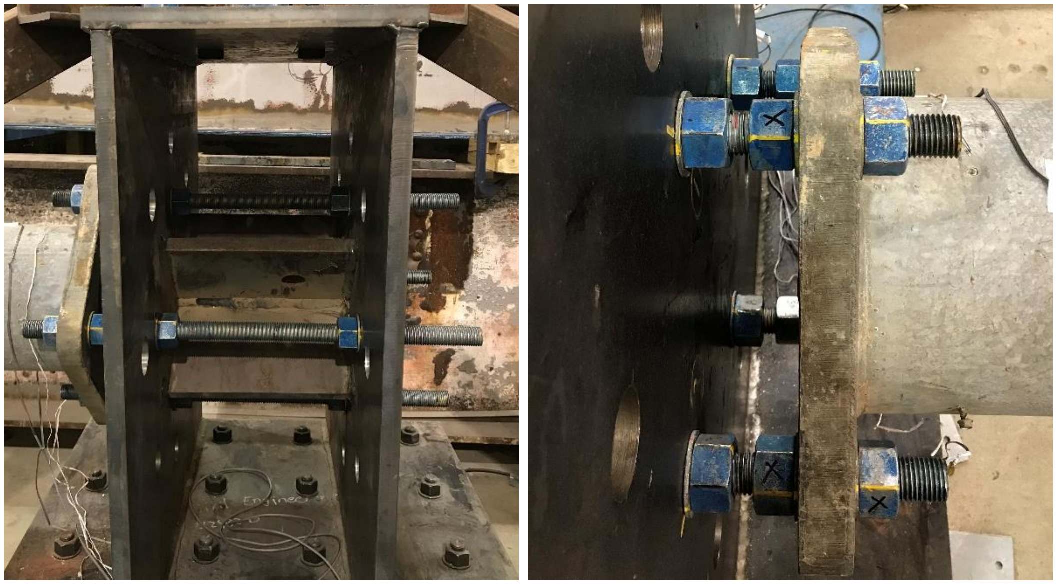


Figure 9. Reaction box fixture for large-scale testing

The fixture block was fastened to two W14x99 sections. The W sections were fastened to the strong floor of the laboratory at three locations, eight ft apart (see Figure 10). Plates were connected to the W sections on the top and bottom to make the beams a closed section. This was done to increase the torsional capacity of the beams and prevent any twisting during the induced vibrations.

Figure 10. Complete view of the test-setup for large-scale testing

Instrumentation

A variable frequency industrial stepper motor was used to induce vibrations in the pole. The motor had a maximum torque capacity of 1.25 ft-lbs (240 oz-in), and was connected to computer for data collection. The motor configuration settings, including the frequency, were input using the software interface on the computer. The motor with eccentric mass on a rotation arm was attached to the end of the pole, as shown in Figure 11. The unbalanced eccentric mass on the motor shaft produced a centripetal force large enough to create displacements or vibrations at the end of the pole.

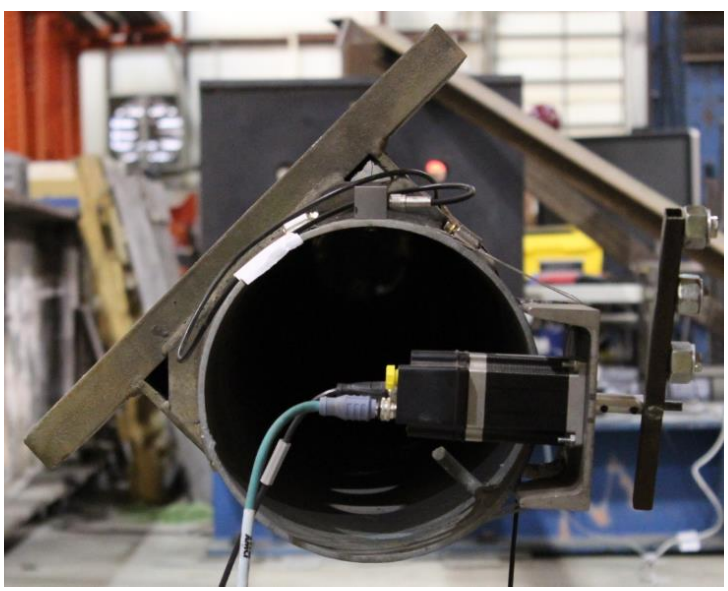


Figure 11. Variable frequency stepper motor attached to the free end of the pole

Bolt strain gages were installed inside 0.078 in diameter pre-drilled holes in the center of the anchor rods to measure axial stresses and pretension in the rod. The holes were drilled 4.25 in deep to ensure that the strain gages were at mid-depth of the double-nut moment connection. Foil strain gages were also installed two ft above the hand hole to measure bending stresses in the pole. A laser distance sensor was installed at the free end of the straight pole to measure free-end deflections. One tri-axial accelerometer was also instrumented at the free end of the straight pole to measure the accelerations due to vibrations. Tilt sensors were mounted on the flat faces of the anchor nut to observe any change in nut rotations. All of the sensors were connected to a data acquisition system for recording and collecting of data.

Test Procedure

Fifteen resonance vibration tests were performed in total. The first test involved vibration testing on the traffic signal with a 15 ft mast-arm. The motor was attached to the mast-arm and the pole was vibrated in resonance in the second mode (fundamental mode of the mast-arm in out-of-plane direction). After the first test, some weld cracks at the box connection between mast-arm and straight pole were observed (see Figure 12). It was later decided to conduct the remainder of the resonance tests on the straight pole vibrating in its first natural mode shape.

Figure 12. Fatigue weld crack at the box connection on the straight pole

The following testing procedure for vibration testing was adopted:

1. All of the anchor rods, nuts, and bearing surfaces were lubricated with beeswax. The anchor rods and nuts were installed to a snug-tight position using a 22 in long open ended wrench on the vertical plates of the box fixture.
2. The anchor rods were further fastened using a turn-of-the nut tightening procedure. The nuts were tightened to 120˚ beyond snug-tight and marked.
3. The straight pole was fastened to the anchor rods in a double nut moment connection with a stand-off distance from the anchor nut fastened to the surface of the foundation fixture plate which was less than one bolt diameter, to reflect specification stand-off requirements. This was done to avoid any bending stresses in the anchor rods due to shear forces or torsional moments (Kaczinski et al., 1998). The anchor nuts were tightened beyond snug-tight position using a turn-of-the-nut tightening procedure

until the required pretension in the rods was achieved. The pretension was measured using the bolt strain gages.

4. The motor was attached to the free end of the straight pole. All of the sensors, including pole strain gages and accelerometer, were installed and instrumented to the data logger system.
5. In the case when the mast-arm was used during test 1, the mast-arm was fastened to the straight pole using structural bolts and nuts. The motor was mounted on the mast-arm. For the remainder of the tests, the motor was mounted on the straight pole.
6. After the installation of the pole, instrumentation of the sensors and mounting of the motor, a pluck test was performed on the structure. The free end of the straight pole was pulled and released. Fast Fourier transform (FFT) analysis of the sensor data were conducted to find the resonant frequencies.
7. The motor was vibrated with the calculated resonant frequency. The eccentric mass on the motor shaft was adjusted until the required vibration stress range was achieved.
8. The nut rotations were recorded throughout the vibration testing using the installed tilt sensors.
9. Any change in nut rotations or the resonant frequency of the pole indicated loss of pretension.

Task 5: Small-scale Vibration Testing

Small-scale testing involved axial vibration testing of a single anchor rod in a double nut moment connection. The testing was performed on a fatigue rated universal testing machine with a 110-kip capacity. The purpose of this task was to verify and validate the results of large-scale testing and also to evaluate the effect of direction of vibration on the loosening of anchor nuts. The rate and amplitude of loading was adjusted to match the results found during field monitoring and large-scale testing.

Test Setup

The anchor rod to be tested was fastened to a base plate in a double-nut moment connection. In order to produce axial vibrations in the connection, the top end of the rod was fastened to the top built-up fixture. Two other holes were drilled in the base plate such that two 1.5 in diameter threaded rods could be fastened to the base plate. The other ends of the 1.5 in diameter threaded rods were fastened to the bottom built-up plate fixture. Both the top and bottom built-up fixtures were clamped in the grips of the fatigue testing machine. Axial vibrations were simulated in the double-nut moment connection using the sinusoidal cyclic forces (alternating tension and compression) produced by the fatigue testing machine. The test-setup was also braced by angles to prevent any lateral movement. A schematic and photograph of the test-setup is shown in Figure 13.

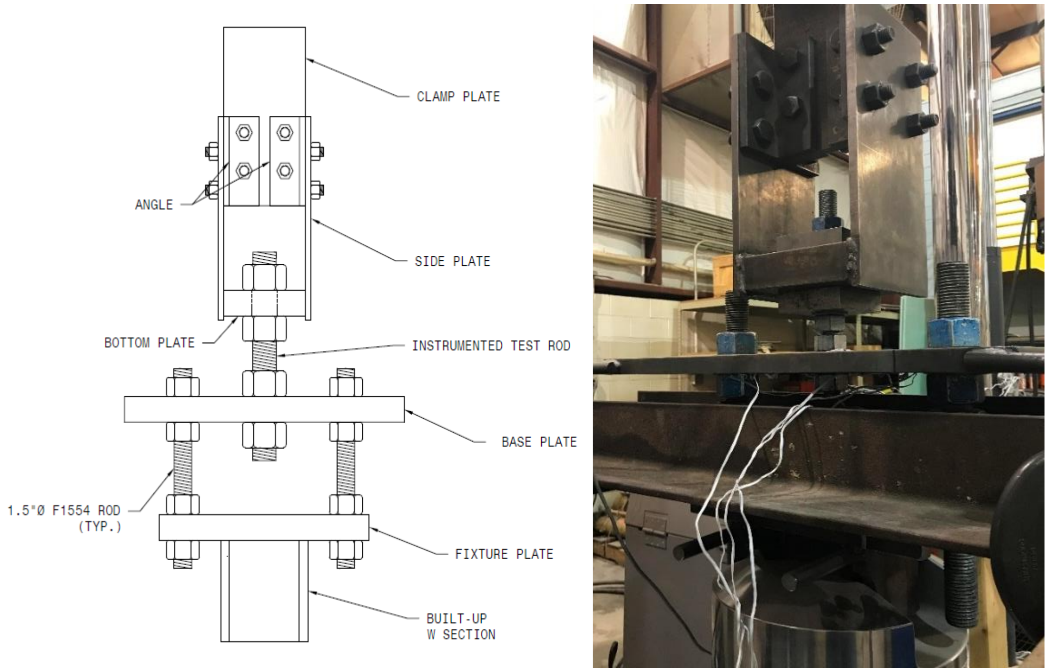


Figure 13. Small-scale test-setup – Schematic (left) and Photo (right)

Instrumentation

Anchor rods with a 1 in diameter of grade 55 were tested in the small scale testing. The anchor rods were instrumented with bolt strain gages. The bolt strain gages were placed into 0.078 in diameter predrilled holes in the center of the anchor rod. The depth of these holes ensured that the bolt strain gage center was at the mid-thickness of the base plate in order to measure maximum tensile stress in the anchor rod. Both the nuts and the flat plate surface were marked during the time of tightening. Strain gages were connected to a data acquisition system for data recording and collection.

Test Procedure

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

1. The anchor rod, nuts, and bearing surfaces were lubricated with beeswax.
2. The anchor rod was fastened to the base plate in a double-nut moment connection using an adjustable wrench. Both the nuts were first snug-tightened using a 15 in long adjustable wrench followed by the tightening of the top nut, resulting in a specific stress based on the results from large-scale testing. The pretension was measured using the bolt strain gage.
3. Both the nuts and the plate were marked.
4. Sinusoidal cyclic loading was applied to the connection using the fatigue testing machine’s software. The loading was increased until the required stress range was achieved. The loading frequency was set at 4 Hz.
5. Any loss in pretension was periodically recorded.

Task 6: Evaluation of Thread Fabrication Tolerance

Thread Terminology

Threads are of two types – internal and external. The term 'internal threads' refers to the threads on the nuts whereas the term 'external threads' is often used for threads on a bolt, rod, or screw. Threads have a triangular profile with the top corner on the threads referred to as crest, whereas the bottom corner is referred to as the root of the threads. The root and the crest are connected by the surface called the flank. The distance measured parallel to the axis of the bolt or nut between the roots or the crests is known as the thread pitch. The distance measured radially between the adjacent root and crest is known as the thread height. The thread pitch and thread height vary with the diameter of the bolt or nut. Finally, the flank angle is the angle between a flank and the axis that is perpendicular to the bolt or nut axis. Thread profiles for a bolt and a nut along with external thread terminology and internal thread terminology can be seen in Figure 14.

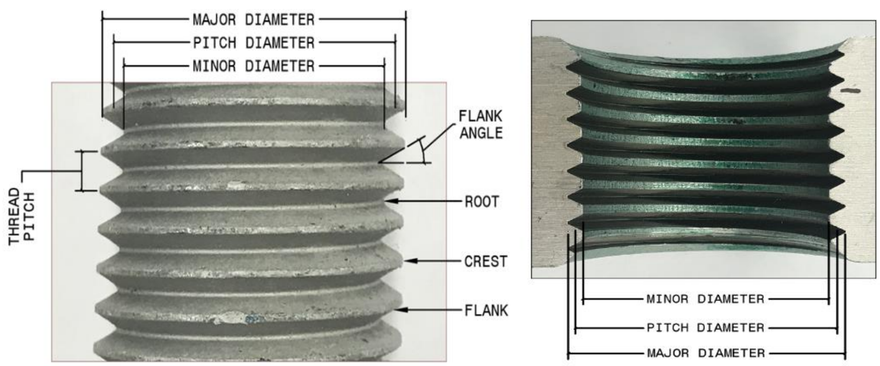


Figure 14. Thread terminology for a bolt (left – external threads) and a nut (right – internal threads)

There are three types of diameters associated with the internal and external threads: major, minor, and pitch diameter. The major diameter is the distance between crests for external threads and the distance between the roots for internal threads (see Figure 14). Similarly, the minor diameter is defined as the distance between roots for external threads and the distance between crests for internal threads. Pitch diameter is defined as the diameter of an imaginary cylinder that passes through the thread profile such that the distance between the adjacent flanks making the crest and the distance between the adjacent flanks making the root are equal (Fastenal 2009). Ideally, the pitch diameter should be halfway between the major and minor diameter.

There are three types of thread series commonly used in structural applications: Unified Coarse (UNC), Unified Fine (UNF), and 8-thread (8-UN). For these three unified inch screw threads, there are six classes of thread fit: 1A, 1B, 2A, 2B, 3A, and 3B. The fit of the threads depends on the tolerance. The higher number refers to a tighter fit. A and B are designated for external and internal threads, respectively.

Tolerances

The anchor rods and nuts used in ancillary structures are commonly galvanized to prevent their corrosion and increase their service life. There are two types of galvanization processes commonly used for fasteners: hot dip galvanizing and mechanical galvanizing. Hot-dip galvanization involves dipping in a molten zinc bath and spinning the specimen until it is coated. This process produces a thick zinc layer, and, hence, the nuts are tapped oversize after their galvanization (Curven, 2011). The nuts are overtapped to make sure they fit the galvanized external threads of the rod. In contrast, mechanical galvanization involves coating with glass media or beads and, as such, is more controlled than the hot-dip galvanization. The resulting coating is uniform and thin. Therefore, the overtapping of the nuts is done before their galvanization. ASTM F1554 and ASTM A563 specify the allowable zinc build up and overtapping allowance for anchor rods and nuts, respectively (ASTM, 2015a; ASTM, 2015b); these limits are shown in Table 2 and Table 3, respectively. It is essential that the anchor nut and rod thread parameters be within the tolerances specified in the ASTM standards to ensure proper fit up and pretension in a connection assembly. A close tolerance fit would not allow for the free turning of the nut onto a rod whereas a loose tolerance fit could potentially lead to loosening of the nuts upon vibration and reduced pretension during tightening.

Table 2. Allowable zinc build-up on ASTM F1554 Anchor Rods (ASTM, 2015a)

Nominal Diameter (in)	Threads/in	Diametrical Zinc Buildup*, in	Anchor Rod Diameter, max (in)	
			Major	Pitch
3/4	10	0.020	0.7682	0.7032
1	8	0.024	1.0220	0.9408
1 1/4	7	0.024	1.2718	1.1719
1 1/2	6	0.027	1.5246	1.4163
2	4.5	0.050	2.0471	1.9028

* These values are the same as the overtap requirements for zinc-coated nuts given in Specification ASTM A563.

Table 3. Overtapping Allowances for ASTM A563 Nuts (ASTM, 2015b)

Nominal Diameter (in)	Threads per in	Diametrical Allowance (in)	Minor Diameter (in)		Pitch Diameter (in)		Minimum Major Diameter (in)
			Min	Max	Min	Max	
3/4	10	0.020	0.662	0.6830	0.7050	0.7127	0.7700
1	8	0.024	0.889	0.9140	0.9428	0.9516	1.0240
1 1/4	7	0.024	1.119	1.1470	1.1812	1.1908	1.2740
1 1/2	6	0.027	1.347	1.3770	1.4187	1.4292	1.5270
2	4.5	0.050	1.809	1.8450	1.9057	1.9181	2.0500

Methodology

Thread parameters of five diameters (0.75 in, 1 in, 1.25 in, 1.5 in, and 2 in) of galvanized anchor rods and nuts were studied to observe if they satisfied the tolerance requirements for galvanization and overtapping as specified in ASTM F1554 and ASTM A563 (ASTM, 2015a;

ASTM, 2015b). The anchor rods and nuts were procured from three suppliers in Virginia. All three suppliers produced threads using the rolling method and used hot-dip galvanizing for the rods and nuts. Anchor nuts procured from the three suppliers were a mix of ASTM A563 grade DH and ASTM A194 grade 2H as per their availability in the market. However, the galvanization and overtapping specifications for ASTM A194 nuts are identical to ASTM A563 nuts (ASTM, 2015b). The anchor rods were grade 55 steel and 1 ft in length. Three heavy-hex nuts for each diameter were procured from each of the three suppliers.

A digital microscope with measurement functions was used for measuring thread parameters on the anchor rods and nuts (see Figure 15). The microscope had a resolution of 0.1 mm or 0.004 in. The lights on the microscope and other external lighting were used to reduce reflection noise and to improve image clarity and edge detection. The major diameter of the rod and the minor diameter of the nut were measured using 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 including thread pitch, thread height, and flank angle were measured using the digital microscope.

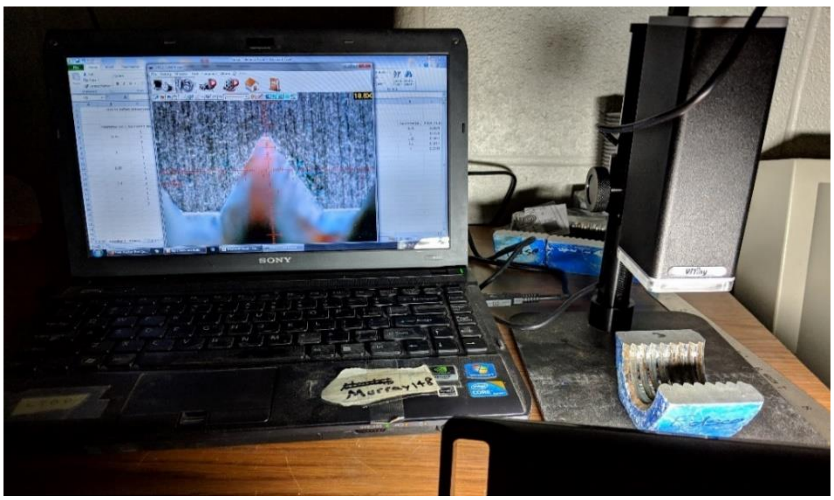


Figure 15. Thread Parameters for a 2 in nut measured under the microscope

Three different thread parameter readings were taken using the digital microscope and calipers along the length of each anchor rod. Heavy hex nuts were cut in half across the corners using a band saw. Readings were taken for one-half of each of the three anchor nuts. The average of these three readings for each diameter from each supplier was compared to the allowable tolerances.

Anchor Rods

The following steps were taken for measuring the different thread parameters on the anchor rods:

1. The major diameter of the anchor rod was measured at a location along the length using the outside jaws of the calipers.

2. A digital microscope and lens were calibrated at the required height of the specimen using a target calibrator (see Figure 16).

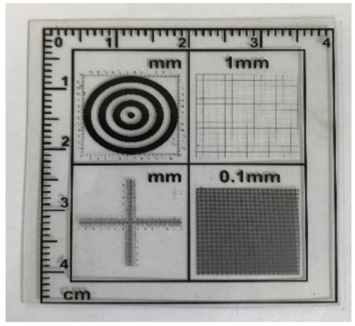


Figure 16. Target Calibrator

3. Once the digital microscope lens was calibrated to the mid-height of the anchor rod, the measurement function was used to measure the thread height, thread pitch, and flank angle of the anchor rod (Figure 17).

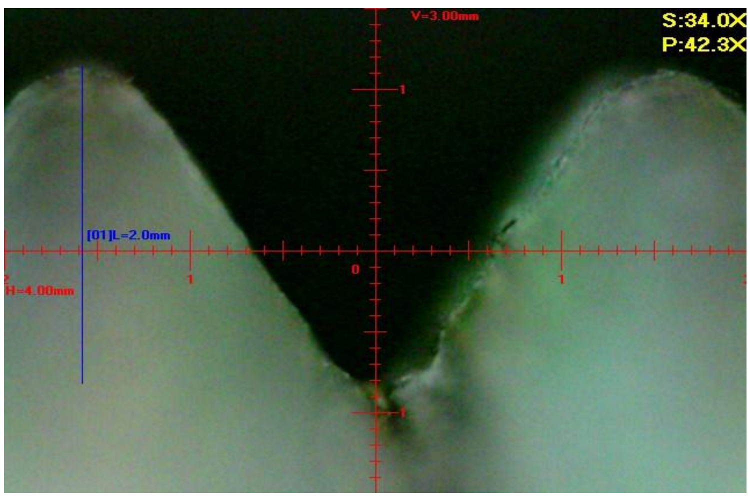


Figure 17. Measurement of the thread height of a specimen under the microscope

4. The pitch diameter was further calculated using the major diameter and the thread pitch calculated previously (see Figure 18). The expression for pitch diameter in terms of the major diameter and the pitch is given in ASME B1.1 (Equation 1) (ASME, 2003). Equation 1 uses simple trigonometric relations and assumes that the flank angle is equal to 30˚. The flank angle measurements during the study were found to be within +/- 0.25˚ and, hence, would have a negligible effect on the final pitch diameter.

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

Equation 1. Equation for calculating pitch diameter using major diameter and pitch for anchor rods

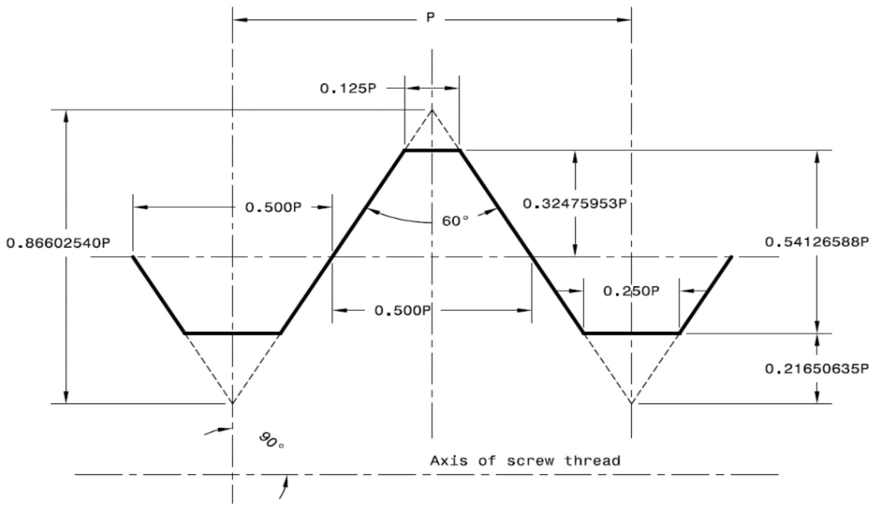


Figure 18. Basic thread profile for unified coarse (UNC) threads (ASME, 2003)

5. The minor diameter of the anchor rod was calculated by subtracting two times the thread height from the major diameter found previously.
6. The same procedure was repeated for two other locations on the same anchor rod. This procedure was further repeated for anchor rods from other suppliers.
7. The average of all the thread parameters readings at the three locations of the anchor rod for each diameter and each supplier were recorded.

Anchor Nuts

The following steps were taken for measuring the different thread parameters on the anchor nuts:

1. The minor diameter of the half cut anchor nut was measured at a particular location along the length using the inside jaws of the calipers.
2. Steps 2 to 3 of the anchor rod procedure involving calibration and measurement of thread height, pitch, and flank angle were performed (see Figure 19).

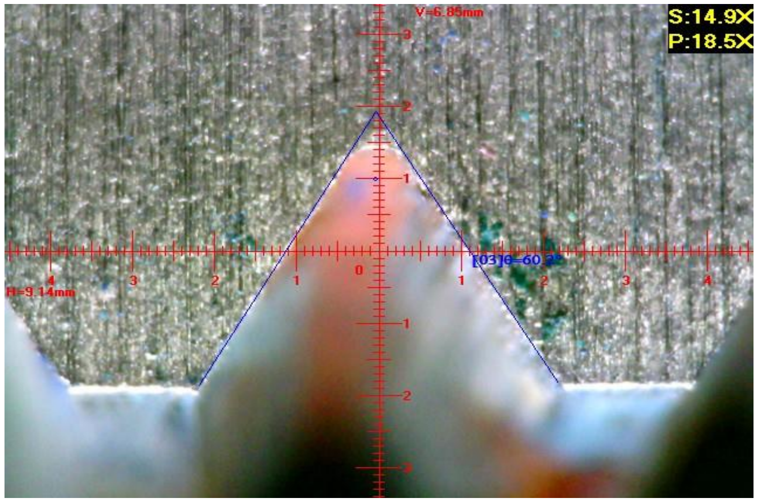


Figure 19. Measurement of the flank angle of a specimen under the microscope

3. Pitch diameter was calculated using the relationship between minor diameter and pitch as given in ASME B1.1 (Equation 2) (ASME, 2003)

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

Equation 2. Equation for calculating pitch diameter using minor diameter and pitch for anchor nuts

4. The major diameter of the anchor nut was calculated by adding two times the thread height to the minor diameter previously determined.
5. The same procedure was repeated for cut halves of the two other anchor nuts and also for the nuts from other suppliers.
6. The average of all the thread parameter readings from three nuts for each diameter and each supplier were recorded.

Task 7: Tightening Procedures for Anchor Nuts on Transformer Base (T-base) Poles

T-base poles and most aluminum ancillary structures use single-nut anchor rod connections at the base. T-base poles are commonly used for aluminum luminaires. An 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 connection for a pole with T-base is shown in Figure 20. There are no prescribed separate guidelines for tightening single-nut anchor rod connections on ancillary structures. At present, NCHRP 469 recommends tightening single-nut anchor rod connections to the same pretension as double-nut moment connections (Dexter and Ricker, 2002). In contrast, AASHTO recommends tightening single nut anchor rod connections on ancillary structures to half of the nut rotations recommended for double nut connections (AASHTO, 2015). There is no guidance regarding tightening of single-nut connections provided in the VDOT Road and Bridge Specifications (VDOT 2016a).

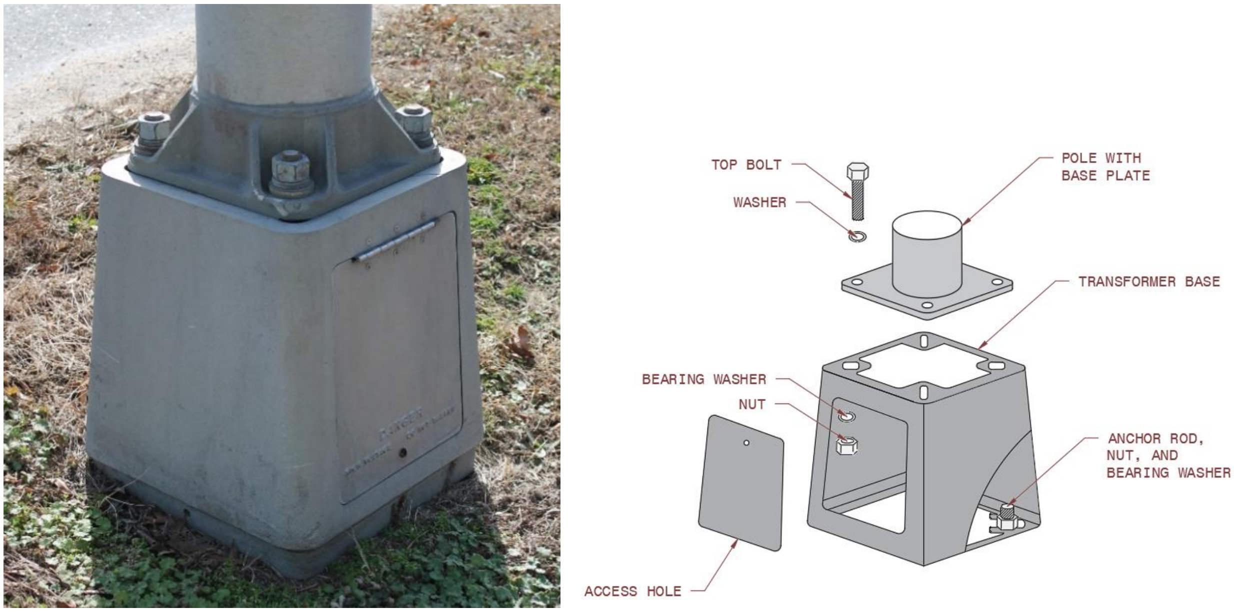


Figure 20. A luminaire with a T-base connection (left) and components including anchor rods (or bolts) inside a T-base (right)

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. 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 21). As seen in Figure 21, it can be challenging to tighten anchor nuts using a hydraulic wrench or torque wrench inside the transformer base due to limited access and electrical wiring. The structural bolts connecting the pole/shoe base to the T-base may be required to be tightened using turn-of-the-nut method as per the shop drawings.

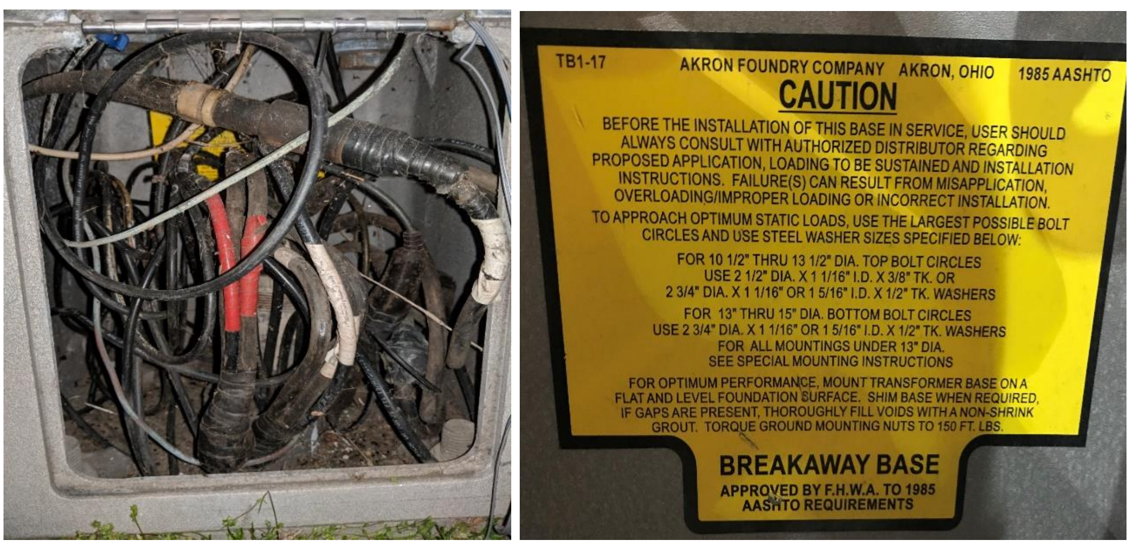


Figure 21. Electrical wiring (left) and manufacturer's instructions for installation (right) inside T-base

Due to 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. Further, some of the good tightening methods identified from the survey were used to perform the tightening study on a T-base in the laboratory.

Test Setup

Four 1 in grade 55 anchor rods were cast inside a 30 in diameter, 24 in deep concrete foundation. The typical detailing given in the VDOT 2016 Road and Bridge Standards was followed (VDOT 2016b). The anchor rods were surrounded by a rebar cage consisting of 12-#8 vertical rebar and 5-#4 rebar ties at 4.5 in on center. The concrete foundation was connected to a 1 in thick A36 grade steel plate using four 0.75 in 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 22.

Figure 22. Formwork for the concrete foundation (left) and T-base with the casted foundation (right)

Instrumentation

Fifty-kip through-hole load cells were used to measure the pretension in the anchor rods. A manual calibrated torque wrench with a torque capacity of 450 ft-lbs was used for tightening the anchor rods on to the T-base. Deep sockets along with extensions were also used for the ease in tightening. The turn-of-the-nut method was used for incremental tightening. The through-hole load cells were initially calibrated in compression using a 400 kip capacity compression testing machine. During tightening, the change in nut rotation was recorded visually using an 180˚ radial gauge. A datalogger was used for monitoring and recording pretension data.

Test Procedure

Each of the four anchor rods was tightened five times in total. Two tightening techniques were used. The first technique involved tightening the anchor rod using a 3 in deep socket from the access hole of the T-base (see Figure 23). The second technique involved tightening the anchor rod using the 3 in deep socket along with a 16 in long extension. The extension was passed through the upper holes for structural bolts for the ease of tightening (see Figure 23).

Figure 23. 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 with the long extension tightening technique. Each test involved tightening the anchor rod in torque increments and recording the corresponding pretension and nut rotations.

Task 8: Evaluation of Inspection Methods

Inspection methods used for determining pretension in the anchor rods installed on ancillary structures were investigated through review of relevant literature. The results from this review are provided in the results section.

Task 9: Snug-tight Study

Testing Procedure and Specimen Matrix

The effect of variable wrench length and force applied on snug-tight pretension in double-nut moment connection was investigated. A base plate was instrumented with bolt strain gages around the anchor hole similar to the instrumentation and calibration described in Task 1.

Beeswax was used as a lubricant. Nineteen students/workers in the lab participated in the tightening study. Multiple participants were chosen so that the effect of variation in force/torque on snug-tight stress could be observed. Participants were asked to read the different definitions of snug-tight condition provided in various specifications (AASHTO 2015; Dexter and Ricker 2002; Garlich and Thorkildsen 2005; MDOT 2014; VDOT 2016a) before testing. Adjustable length ratchets were used to account for the variation in torque due to change in moment arm. The lengths chosen were close to the typical open-end wrench lengths found in the market for the particular diameter of the nut. The specimen matrix for the snug-tight study is shown in Table 4. Two diameters of anchor rods (1 in and 2 in) were tested in this phase. Each participant was asked to snug-tighten the double-nut moment connection with three different wrench lengths. Bolt strain gages in the calibrated base plate were used to measure pretension induced due to the snug-tightening procedure.

Table 4. Specimen Matrix for Snug-tight study

Grade	Anchor Rod Diameter (in)	Wrench Length (in)
55	1	12, 16, 20
	2	24, 32, 40

Task 10: Development of Nut Tightening Procedures

Results were synthesized into recommendations for changes in current VDOT tightening specifications for double-nut moment connections and single-nut connections. Recommendations were also provided on proper tightening and methods to prevent loosening of anchor nuts on ancillary structures. The detailed changes and recommendations are provided in the Appendix.

RESULTS AND DISCUSSION

Task 1: Literature Review

The current tightening procedures for double-nut moment connections specified in the Federal Highway Association (FHWA) guidelines, and American Association of State and Highway Transportation Officials (AASHTO) specifications were produced by National Cooperative Highway Research Program (NCHRP) report 469 (AASHTO, 2015; Dexter and Ricker, 2002; Garlich and Thorkildsen, 2005). Turn-of-the-nut tightening procedures are recommended for tightening of anchor rods onto foundations in ancillary structures (AASHTO 2015; Dexter and Ricker 2002; Garlich and Thorkildsen 2005; VDOT 2016a). The anchor nuts are required to be tightened incrementally up to a specific rotation past snug tight, and are dependent on the diameter and grade of the anchor rod (see Table 5). The specified nut rotations given in Table 5 ensure that the anchor rod achieves minimum installation pretension (P), which is below the yield strength of the anchor rod grade. After final tightening, nut rotations are recommended to be verified by applying a verification torque. The inability to achieve the verification torque may indicate stripping of the threads (AASHTO 2015; Garlich and

Thorkildsen 2005). The anchor rods are also recommended to be retightened using 110 % of verification torque 48 hours after installation to overcome any initial relaxation (AASHTO 2015; Garlich and Thorkildsen 2005). VDOT specifications only recommend verifying the nut rotation of a minimum of every other anchor rod using a verification torque right after the tightening sequence (VDOT 2016a). However, there are no guidelines on retightening after 48 hours (VDOT 2016a). The equation for the verification torque was derived by Till and Lefke (1994) and further adopted in the different tightening specifications (Equation 3).

Table 5. Recommended top nut rotations for turn-of-the-nut tightening (AASHTO 2015)

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

UNC = United National Coarse

$$T = 0.12dP$$

Equation 3. 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).

Double-nut moment connections are capable of resisting moments and perform better than single-nut connections in resisting dynamic loads (Kaczinski et al., 1998). Single nut connections are used primarily for aluminum luminaires whereas double-nut connections are common for traffic signals, sign structures, and high-mast towers. A typical double-nut and single-nut connection on ancillary structures are shown in Figure 24 and Figure 25, respectively.

The anchor nuts on ancillary structures are tightened in a star pattern to ensure appropriate tightening occurs uniformly throughout the base plate and ensures even load distribution.

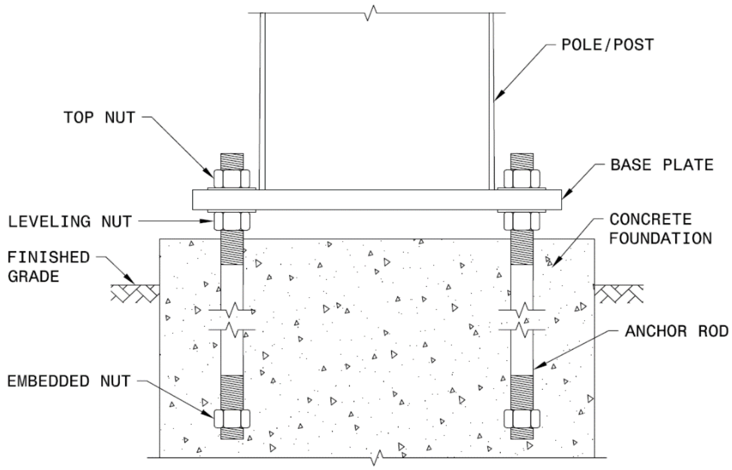


Figure 24. A typical double-nut moment connection on ancillary structures

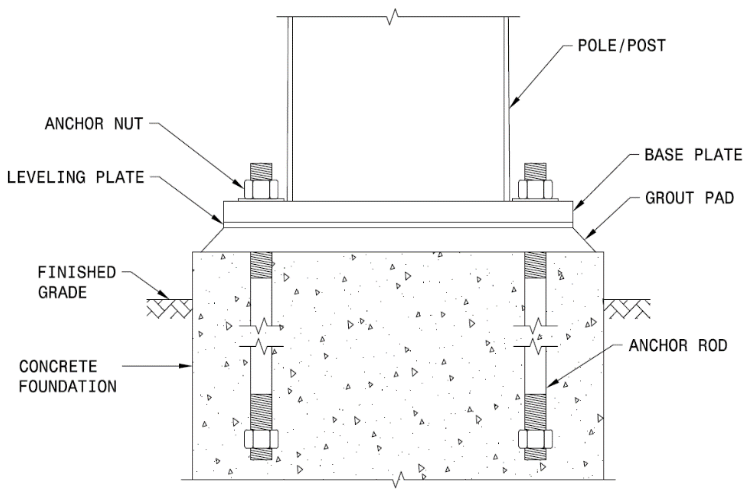


Figure 25. A typical single-nut connection on ancillary structures

There are a few discrepancies in the existing literature and tightening 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 still are grouped under the same category for recommended nut rotations (AASHTO 2015) (see Table 5). The 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 to 85-100% of the yield strength if the bolts are exposed to dynamic or vibration loads (Bickford, 2008). FHWA guidelines recommend a minimum installation pretension of 50% of F_u for grade 36 rods and 60% of F_u for other grades which is just below the minimum specified yield strength of the anchor rods. On the other hand, AASHTO specification requirements for minimum installation pretension are lower (i.e. 50% of F_y for grade 36 rods and 60% of F_y for other grades). Past research suggests that anchor nut loosening is primarily due to over-tightening (yielding) of rods (Hoisington and Hamel 2016) and not due to the under-tightening during installation (James et al. 1996). Therefore, anchor rods in a double-nut moment connection should be tightened to ensure there is no under-tightening or over-tightening (yielding) of the rods.

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 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 in 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). Therefore, 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). They 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 in diameter) or under-tightening of larger anchor rods (> 1.5 in 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 in to 100 in.

A majority of the research on ancillary structures has been related to fatigue and weld crack issues. Very few research projects have investigated the loosening aspect of anchor nuts specifically. As part of a recent research project, a large scale-test of a straight pole from the Minnesota Department of Transportation (MnDOT) Type 5 signpost was conducted (Chen et al., 2018). Twelve grade 55 anchor rods were tightened to 75% yield as per the specifications. The signpost was loaded cyclically at 1 Hz using an actuator at the free end. The target axial stress of 6 ksi in the rods was determined as a result of field monitoring data. Two of the twelve nuts were found loose after only 600 cycles of a 6 ksi stress range. This 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. No loosening was found when the pole was cycled at the common vibration stress range of 1 ksi.

Task 2: Tightening Procedures for Double Nut Moment Connections on Ancillary Structures

Yield and Tensile Strength

In total, 100 anchor rods were tested as part of the tightening study. The minimum specified yield and tensile strength of all three grades of anchor rods are shown in Table 6. The maximum values of actual material yield and tensile strength of the anchor rod specimens as reported in the supplied mill certifications are shown in Table 7.

Table 6. Minimum specified yield and tensile strength of ASTM F1554 anchor rods (ASTM, 2015a)

Grade	Minimum Yield Strength (ksi)	Minimum Tensile Strength (ksi)
36	36	58
55	55	75
105	105	125

Table 7. Maximum reported yield and tensile strength of the anchor rods from mill certifications

Rod Diameter (in)	Maximum Reported Rod Strength (ksi)					
	Grade 36 Anchor Rod		Grade 55 Anchor Rod		Grade 105 Anchor Rod	
	Yield Strength	Tensile Strength	Yield Strength	Tensile Strength	Yield Strength	Tensile Strength
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

Minimum Installation Pretension

The minimum installation pretension (P) is a percentage of the minimum specified tensile strength per the current tightening guidelines in FHWA and NCHRP 469 (Dexter and Ricker 2002; Garlich and Thorkildsen 2005). The percentage is fixed such that the minimum installation pretension value is less than yield strength in order to prevent any yielding of the anchor rods during tightening. The specified minimum installation pretension as a percentage of yield strength is shown in Table 8. The ratio P/F_y is approximately 80% for grade 36 and 55 rods whereas it is approximately 70% for the grade 105 rods.

Table 8. Minimum installation pretension as a percentage of yield strength (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

F_y = yield strength; F_u = tensile strength; P = minimum installation pretension

Grade 55 – 1 in Diameter Anchor Rods on Steel Base Plate

Results for six grade 55, 1 in anchor rods tightened on steel base plate are discussed in this section. The remainder of the specimen grades and rod diameters were performed in similar manner; their results are discussed in subsequent sections. Three parameters including nut rotation, pretension, and applied torque were recorded during the turn-of-the-nut tightening procedure. The top nut was tightened incrementally beyond the snug-tight condition until there was a minimal change in pretension corresponding to large change in nut rotation, which indicated yielding of the rod. The pretension vs. nut rotation curve for all six rods is shown in Figure 26 and indicates relatively linear behavior until 70˚, after which the change in slope indicates yielding of the rods. All the rods yielded around 62.5 ksi (see Figure 26). However, the mean nut rotation corresponding to the specified yield strength of 55 ksi was found to be approximately 60˚. Additionally, the mean nut rotation corresponding to minimum installation pretension of 0.6 F_u or 80% of F_y (45 ksi) was found to be 49˚ as opposed to currently specified turn-of-the-nut requirement of 120˚ in the FHWA guidelines (Garlich and Thorkildsen 2005) and AASHTO specifications (AASHTO 2015).

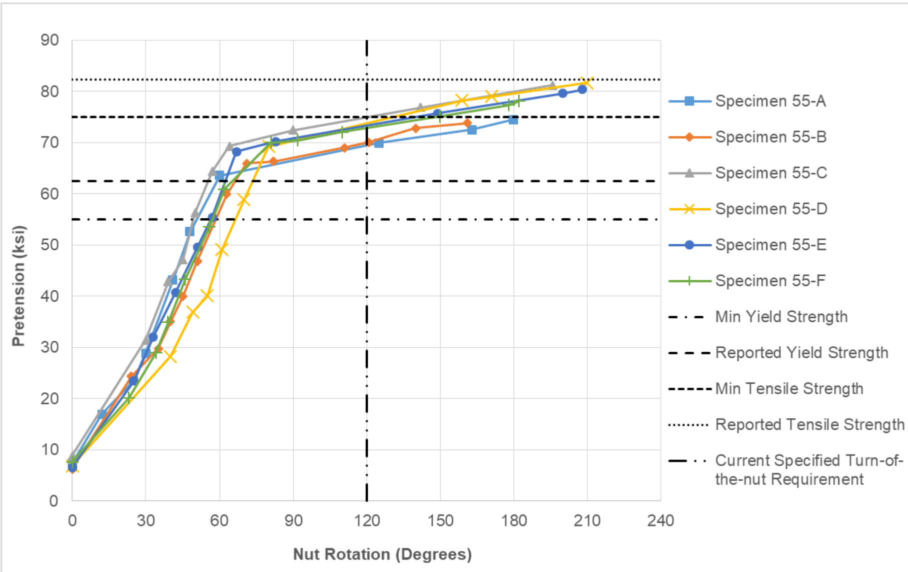


Figure 26. Pretension vs. Nut Rotation curve for grade 55 – 1 in anchor rods on steel base plate

The relationship between pretension in the rod and applied torque was also analyzed. The overall relationship between pretension and torque was similar to the relationship between pretension and nut rotation. The behavior was linear until the rods reached their maximum reported yield strength of 62.5 ksi (see Figure 27). There was more scatter observed in the pretension vs. torque curve as compared to the pretension vs. nut rotation curve. This was due to the dependency of the applied torque on lubrication and friction between the components. The snug-torque for each of the anchor rods was applied using a manual torque wrench and, hence, its values were not plotted in Figure 27.

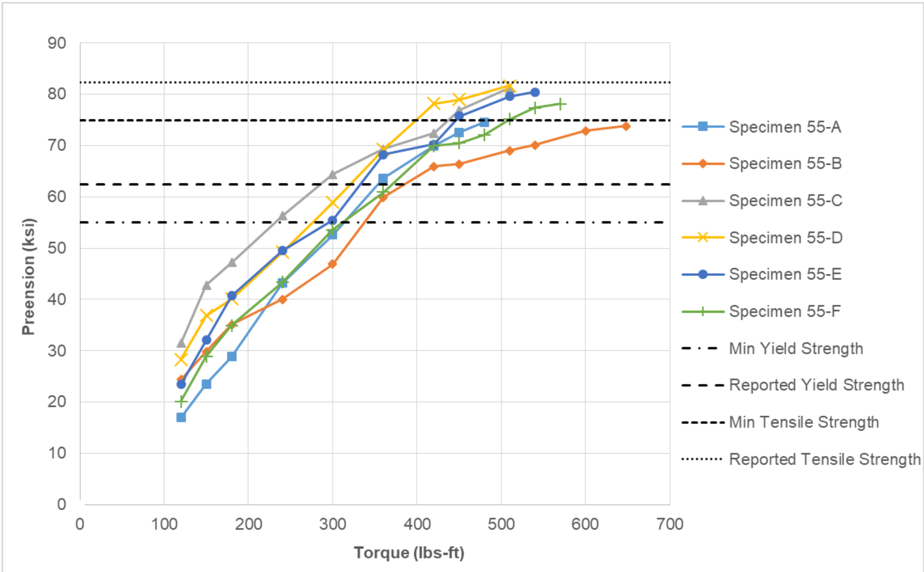


Figure 27. Pretension vs. torque for grade 55 – 1 in anchor rods on steel base plate

Effect of Base Plate Material

One in. diameter anchor rods were tightened on both steel and aluminum base plates. This was done to analyze the effect of base plate material on the tightening procedures and nut rotations during tightening. The pretension vs. nut rotation curve for all of the 1 in diameter anchor rods tested is shown in Figure 28. All of the tested rods behaved similarly (approximately same initial slope) until their respective yields. However, all the anchor rods tightened on the aluminum plates produced relatively smaller pretension values as compared to the ones tightened on steel base plates. This difference could be explained due to the small differences in the calibration slopes of steel plate and aluminum plate. However, the observed difference between the behaviors of anchor rods tightened on the two base plate material was small and would not have a significant impact on the overall results. Hence, it can be concluded that the turn-of-the-nut tightening procedures are independent of the material of the base plate. It was also observed that grade 36 and 55 behaved similarly to each other, which is indicated by the overlapping curves in Figure 28.

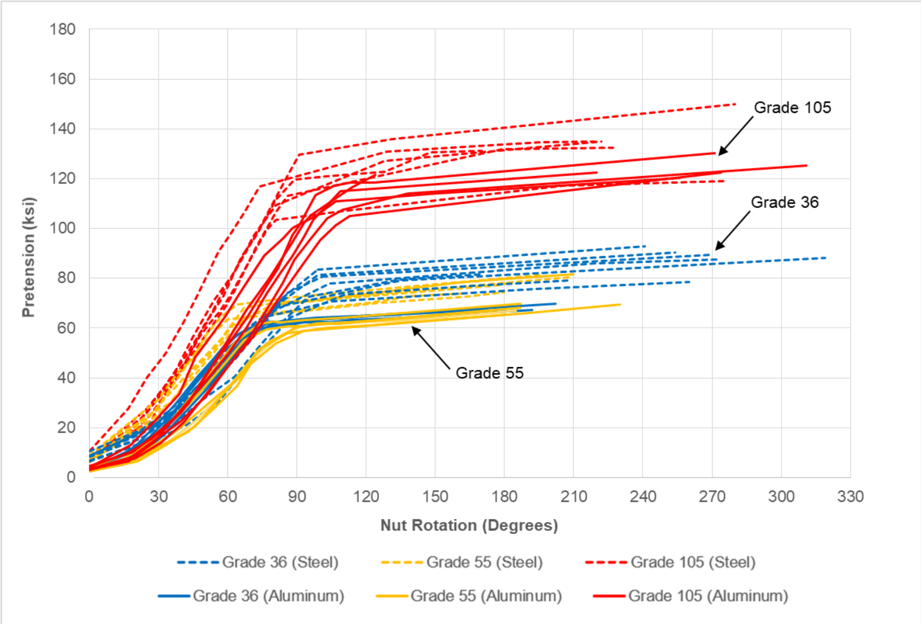
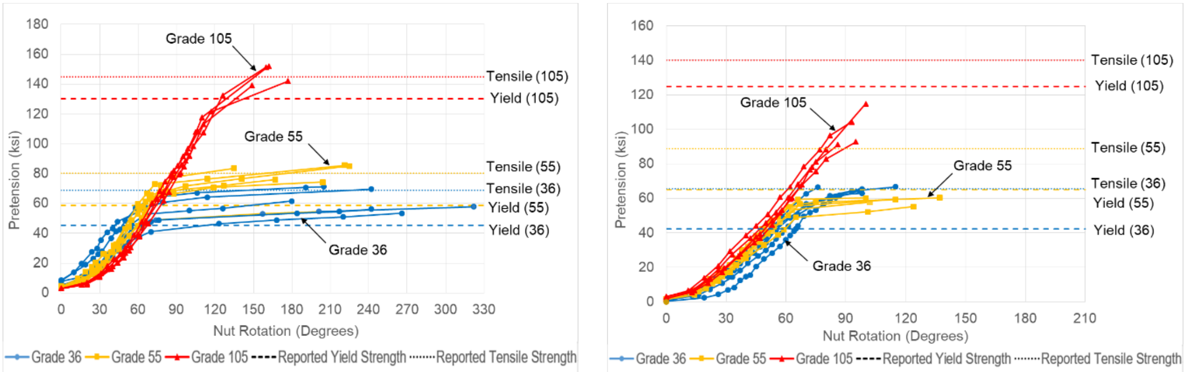


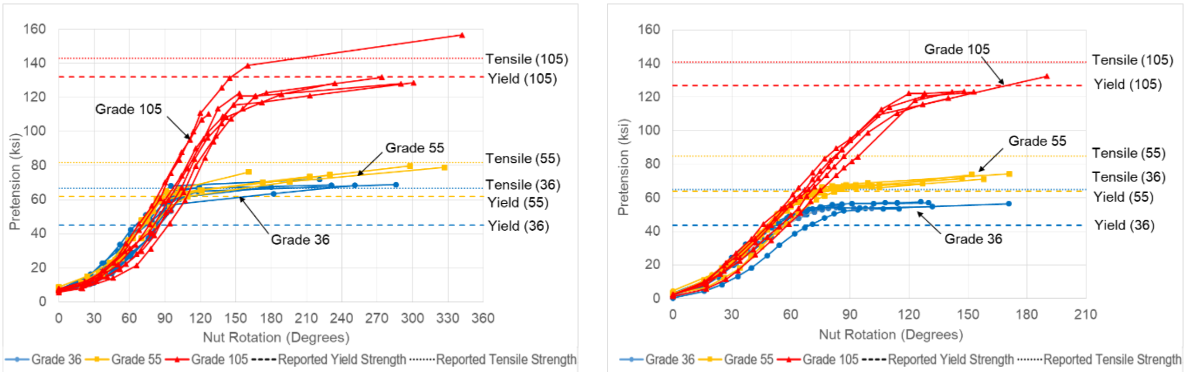
Figure 28. Pretension vs. nut rotation curve for 1 in diameter anchor rods

Pretension vs. Nut Rotation Curves

Four other combinations of anchor rods and base plate were tested: 1.5 in diameter anchor rod on steel base plate, 2 in diameter anchor rod on steel base plate, 0.75 in diameter anchor rod on aluminum base plate, and 1.25 in diameter anchor rod on aluminum base plate. The pretension vs. nut rotation curves for all the four combinations are shown in Figure 29. The curves for anchor rods of all steel grades remained linear until their respective yield strengths for each combination. The bilinear behavior of grade 36 and 55 anchor rods was very similar. Grade 105 – 2 in diameter anchor rods did not yield due to the large amount of tension required for yielding (Figure 29 (b)). Some local yielding around the aluminum base plate holes was observed during tightening. This behavior is unlikely to occur during the installation as the rods should only be tightened to a percentage of yield strength, rather than the extreme loading applied during the test.



(a) (b)



(c) (d)

Figure 29. Pretension vs. nut rotation curves for (a) 1.5 in diameter rods on steel base plate (b) 2 in diameter rods on steel base plate (c) 0.75 in diameter rods on aluminum base plate (d) 1.25 in diameter rods on aluminum base plate

Observed Nut Rotations

Similar to the example calculations shown for grade 55 – 1 in diameter anchor rods in the previous section, the mean nut rotations required to produce the required minimum pretention for each anchor rod-base plate combination were statistically determined (see Table 9). The minimum installation pretension values for grades 36 and 55 were taken from the current specifications, but the minimum installation pretension was increased to 0.7*F_u (which is equivalent to 0.8*F_y) for grade 105 anchor rods.

Table 9. Observed mean nut rotations and corresponding installation pretension

Diameter of rod (in)	Base plate	Nut rotation beyond snug-tight (˚), Mean (2 times standard deviations)			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)			

F_u = tensile strength

A simplified version of Table 9, which divides the anchor rods into those with diameters of less than 1 in and those equal to or greater than 1 in is shown in Table 10. This table provides the observed top nut rotations in increments of 15˚ for two groups of anchor rods, differentiated by rod diameter. The average scatter, statistically defined as two standard deviations, was found to be approximately 15˚ (Table 9). Therefore, a tolerance of +15˚ was included in these synthesized observed nut rotation values in Table 10 which should allow for over-tightening during snug-tightening if any.

Table 10. Observed top nut rotations for double-nut moment connections in increments of 15˚ depending on anchor rod diameter

Diameter of anchor rod (in)	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˚			

F_u = tensile strength

Observations and Findings

Minimum Installation Pretension

All of the grade 105 anchor rods yielded in the range of 100-120 ksi during testing, which is greater than the $0.6*F_u$ (75 ksi) value of minimum installation pretension as recommended in the FHWA tightening guidelines. Therefore, as discussed in the previous sections, the minimum installation pretension of $0.6*F_u$ for grade 105 anchor rods in the FHWA guidelines is inadequate. Having consistent P/F_y ratios of 80% for all three grades of anchor rods would be beneficial because it would align with the recommended minimum installation pretension used for high strength bolts that are subjected to dynamic or vibration loads as specified in Research Council of Structural Connections specification (RCSC 2014).

Observed Over-Tightening and Under-Tightening

The observed nut rotation values corresponding to the minimum installation pretension shown in Table 10 were compared to the currently specified nut rotation values in the tightening specifications (see Table 5) to observe any instances of over-tightening and under-tightening as per the current specifications (see Table 11). From the comparison, Grade 55 anchor rods (< 1.5 in) were observed to be over-tightened by at least 45˚ on average. These rods are required to be tightened to 120˚ as per the current specifications but the test data showed that 75˚ nut rotation beyond snug-tight is sufficient for achieving the required minimum installation pretension. Similarly, the smaller diameter grade 105 anchor rods (> 1 in and < 1.5 in) were observed to be over-tightened by 30˚ on average. Also, the average nut rotations to produce the minimum installation pretension for larger diameter grade 105 anchor rods (> 1.5 in) were found to be close to 90˚ as opposed to the currently specified value of 60˚.

Table 11. Observed over-tightening and under-tightening

Anchor rod diameter (in)	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˚)

Grouping of Anchor Rod Diameters

The test results showed that all anchor rods smaller than 1 in in diameter behaved similarly to each other. This is in contrast to the current specifications, which group the anchor rods into two categories: smaller diameter (≤ 1.5 in) and larger diameter (> 1.5 in) (see Table 5). Based on the test results, a more appropriate grouping of the anchor rod diameter is those less than 1 in and those greater than or equal to 1 in diameter as shown in Table 10.

Separate Nut Rotations for Grade 55 and 105

The current specifications provide the same nut rotations for grade 55 and 105 anchor rods (see Table 5). As discussed in the previous sections, grade 55 and 105 have different target pretension values and, hence, these pretension values cannot be achieved using the same nut rotations. Using the same nut rotation for grade 55 and 105 anchor rods can lead to over-tightening or under-tightening as observed during testing. Therefore, separate nut rotations were tabulated for both of these grades as indicated in Table 10.

Effect of Snug-Tight and Grip Length

The effect of varying grip length was not included in this study. The grip length (base plate thickness) was equal to the diameter of the anchor rod throughout the testing. This is similar to common industry practice. Moreover, the effect of grip length is negligible when base plate thickness (grip length) is less than double the diameter of the anchor rod (Chen et al., 2018). Significant over-tightening or under-tightening as a result of snug-tight pretension is a concern and will be discussed in detail in Task 9. The snug-tight pretension was observed to be in the range of 1 to 11 ksi during the tightening study. The maximum and minimum values of snug-tight pretension observed during the tightening study are summarized in Table 12. However, +15˚ tolerances associated with the observed nut rotations should account for overtightening during snug-tightening if any.

Table 12. Minimum and maximum values of snug-tight pretension

Diameter of rod (in)	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

Task 3: Field Monitoring

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. The different field monitoring results are discussed in detail in the following sections.

Modal Frequencies and Damping Ratios

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 and frequency spectrum for pluck test 1 in the Y-direction performed on the traffic signal and luminaire are shown in Figure 30 and Figure 31, respectively.

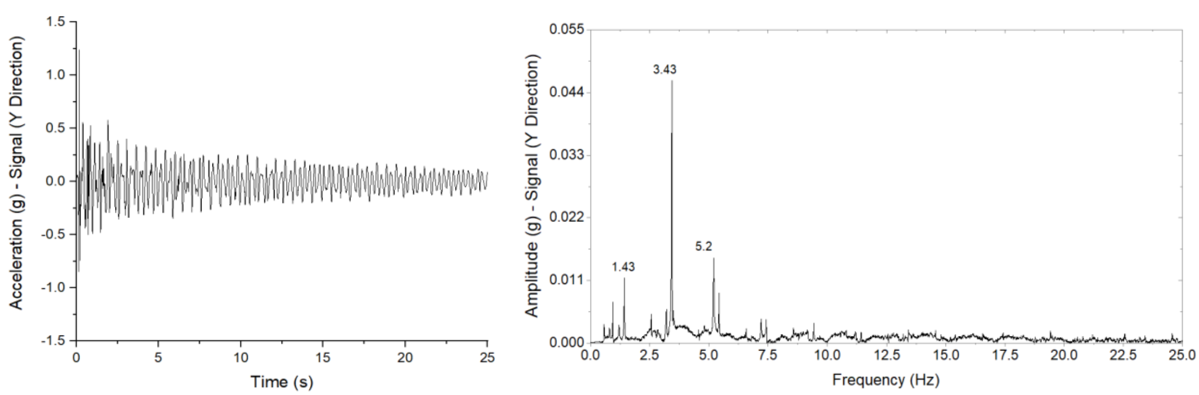


Figure 30. Acceleration time history (Left) and frequency spectrum (Right) for the pluck test 1 performed on traffic signal in Y direction

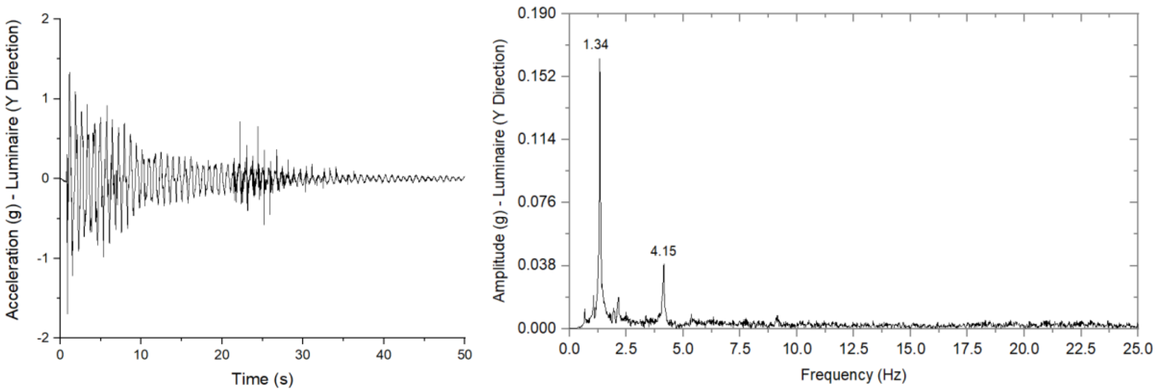


Figure 31. Acceleration time history (Left) and frequency spectrum (Right) for the pluck test 1 performed on luminaire in Y direction

The modal frequencies for the traffic signal and the light pole from the FFT analysis are compiled in Table 13 and Table 14, 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 13. 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[a]	5.2
2		1.42	3.41[a]	5.18
1	Z	NA	3.48	5.76[a]
2		1.48	3.47[a]	5.76[a]

[a] – denotes value represents the dominant modal frequency

Table 14. Modal Frequencies for the Luminaire

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

[a] – denotes value represents the dominant modal frequency

The half-power bandwidth method was used to calculate the damping ratios for each 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 √2 (Figure 32). Half-power frequency points were determined on either side of the peak (modal) frequency. The damping ratio was calculated using Equation 4.

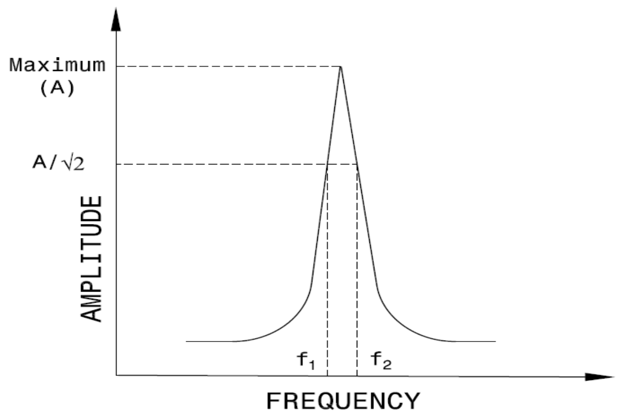


Figure 32. Half-power Bandwidth method

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

Equation 4. Damping ratio formula from Half-power Bandwidth method

Where
ξ = damping ratio
f_1 and f_2 are the frequency points in the 'Amplitude vs. Frequency' curves, as shown in Figure 32, corresponding to an amplitude equal to peak value divided by √2

The damping ratios calculated for the traffic signal and the luminaire using the bandwidth method are shown in Table 15 and Table 16, 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.

Table 15. 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 16. 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

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 33. 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 33). 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%). The SW direction was the same as the Z direction with respect to the orientation of the poles.

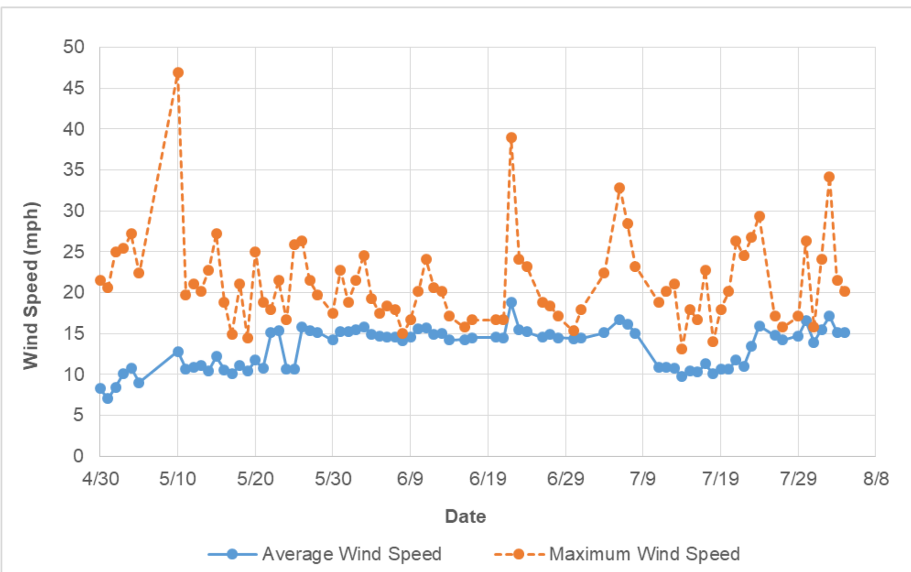


Figure 33. Average and maximum wind speed variation at the location of instrumented poles

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 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.

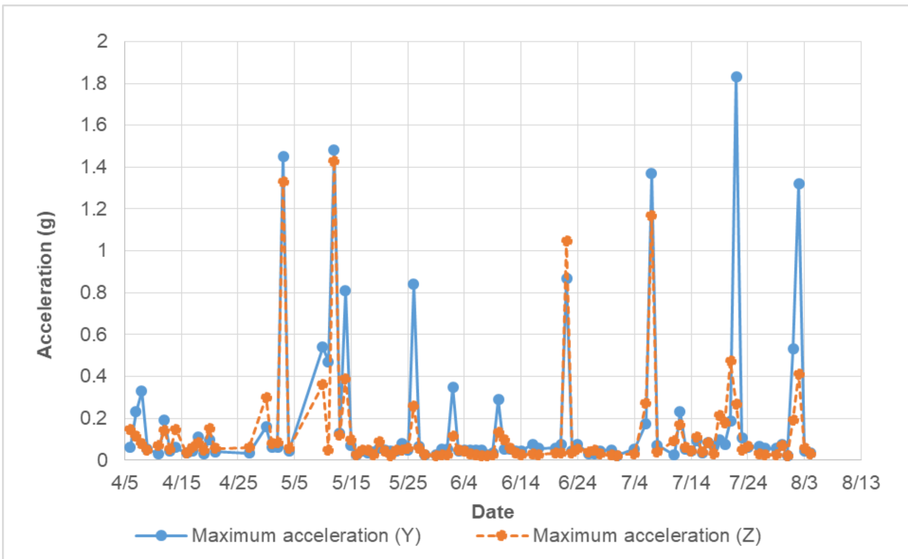


Figure 34. Maximum daily acceleration for the traffic signal

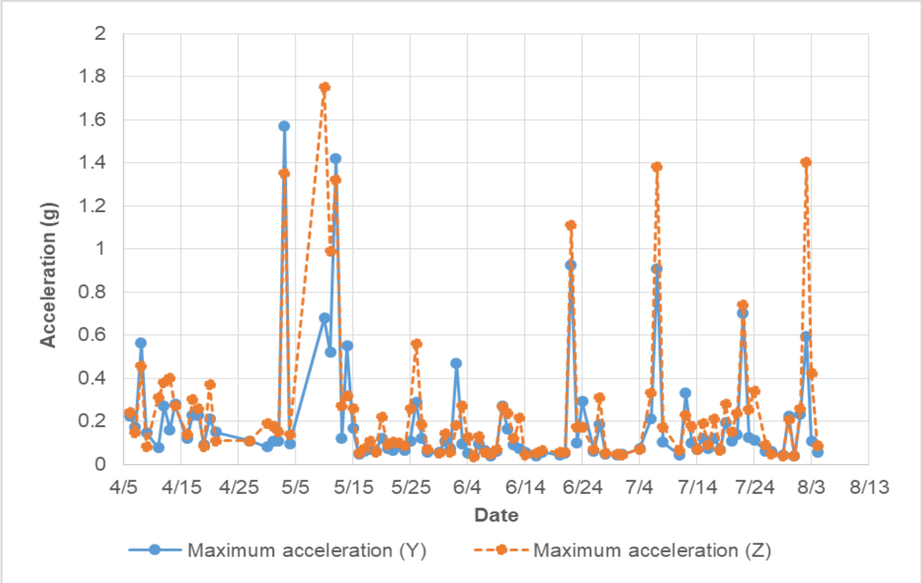


Figure 35. Maximum daily acceleration for the luminaire

Although the majority of wind was blowing along the Z direction, the acceleration data suggests that vibrations were still experienced in both of the principal directions. 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. Most of the higher modes (2nd or higher) are 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). It is very likely that vortex shedding and galloping took place during the four months since the majority of wind speeds were low frequency in the range of 15-35 mph.

Anchor Rod Stress Data

The maximum daily bending stress values for both structures were converted into anchor rod axial stress using bending moment and stress relationships ($\sigma = My/I$). Maximum daily rod stress values of the traffic signal from April to July are shown in Figure 36. Maximum daily rod stress for the traffic signal was in the range of 0.5-4.5 ksi in either direction (see Figure 36). The maximum value of rod stress 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 of the directions were similar to each other. However, the maximum daily axial rod stress recorded in the luminaire was more prevalent in the Z direction as compared to the Y direction (see Figure 37). The overall range was 0.25-3.5 ksi in both directions. The maximum value of axial rod stress 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 months.

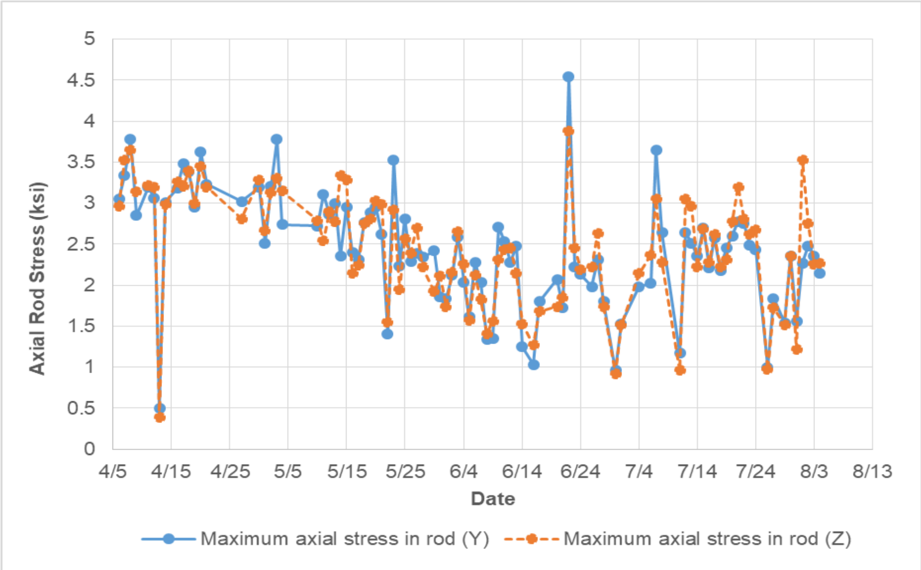


Figure 36. Maximum daily axial rod stress for the traffic signal

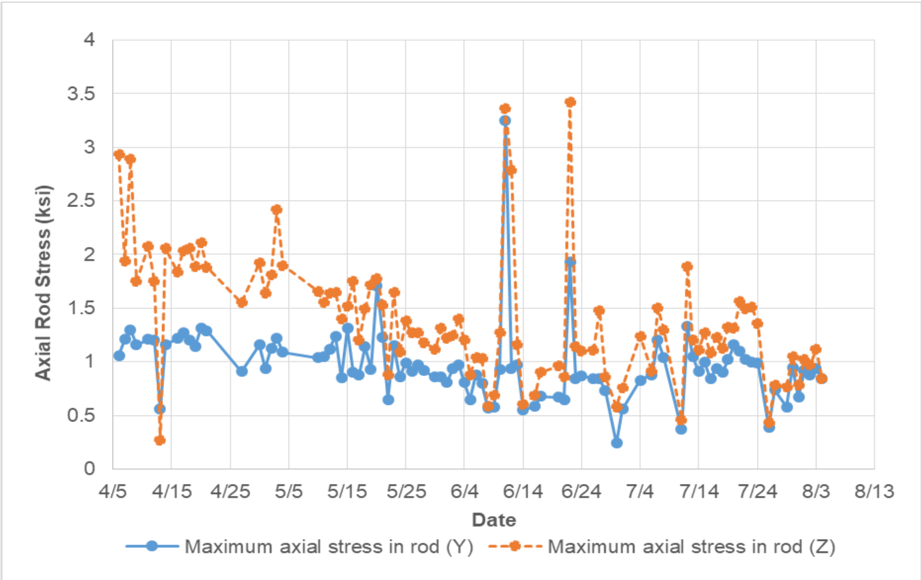


Figure 37. Maximum daily axial rod stress for the luminaire

Stress Histograms

A rainflow-count algorithm 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 contribution greater than 0.1% vibration cycles were considered significant. For the traffic signal, the maximum significant stress range observed was 5 ksi. 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). The luminaire experienced 86,500 cycles at a 3 ksi stress range. The majority of cycles 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.

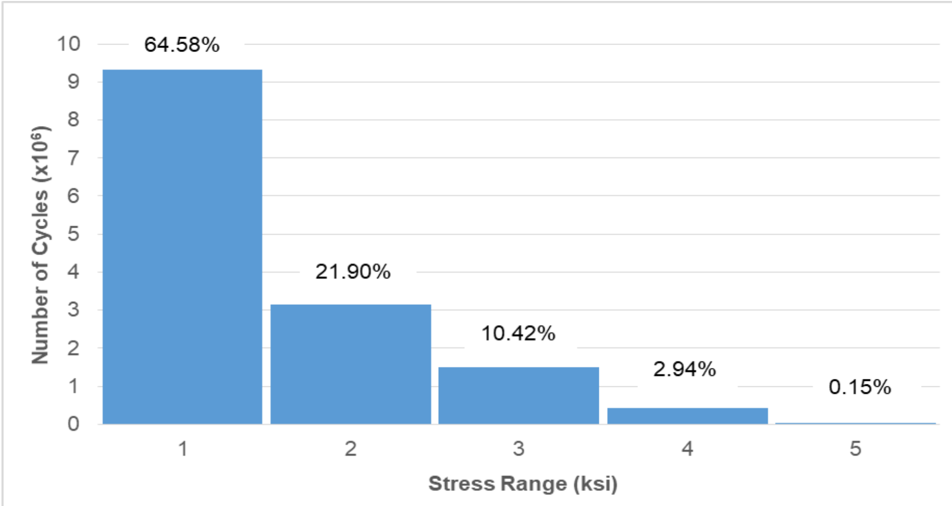


Figure 38. Rod axial stress range histogram for traffic signal in Z direction

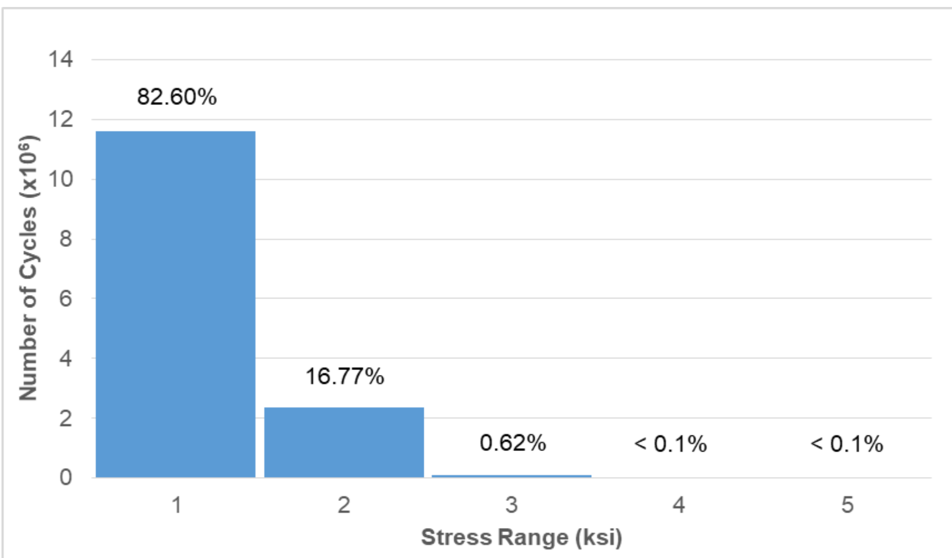


Figure 39. Rod axial stress range histogram for luminaire in Z direction

The stress range data was extrapolated over 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 determined for both 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 5 (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.

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

Equation 5. Equation for effective stress range (AASHTO 2011)

where
γ_i = Percentage of cycles at a particular stress range
Δf_i = stress range

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 suggestive of occurrence of phenomenon like vortex shedding and galloping along with natural gusts.
3. The damping ratios for the luminaire were more than double that of the traffic signal.
4. The low stress ranges (< 5 ksi) contributed to the majority of the vibration cycles in both structures. The stress histogram data for the four months was extrapolated and it was determined that the traffic signal experiences approximately 5 million cycles of 4 ksi stress range in four years.
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.

Task 4: Large-scale Vibration Testing

Testing Configuration and Modal Frequencies

The first large-scale test involved vibrating the pole with the mast arm in its fundamental out-of-plane mode. This fundamental mode is also the second mode of the pole with the mast arm. After vibrating the pole for 600,000 cycles (including the trial tests), a fatigue crack was observed on the welded connection between the mast arm and the straight pole (as shown in Figure 40). The mast arm could no longer be vibrated in resonance, and, hence, from test 2 onward, the straight pole was vibrated in its fundamental mode in the vertical direction, with no mast arm attached (refer to Figure 11). The testing configuration, modal frequencies, mode shapes, and vibration direction of all the tests are shown in Table 17. Modal frequencies were different for each vibration test due to different pretension in anchor rods (different joint stiffness). This can also be seen from the range of the modal frequencies shown in Table 17.

Figure 40. Fatigue crack in welded connection between reaction box and straight pole

Table 17. Testing configuration, modal frequency, and vibration direction of the vibration tests

Test No.	Testing Configuration	Modal Frequency	Mode Shape	Vibration Direction
1	w/ mast arm	5.68	1st out-of-plane mode of mast arm	Perpendicular to plane to mast arm and pole
2-14	straight pole	4.6 - 4.74	1st mode of straight pole	Vertical

Experimental Test Results

For all of the tests, the pole was vibrated at its resonant frequency, and any change in nut rotation/pretension was recorded. Sometimes, there was a change in frequency (or stiffness) due to the development of weld cracking or loosening of the nuts. Both of these cases were observed during testing. Since the pole came out of resonance when one of these occurred, the stress range decreased. Therefore, in order to account for multiple stress ranges, an effective stress range was determined. A rainflow algorithm was used to convert the rod tensile stress data during vibration testing into a histogram of stress and corresponding cycles. The equation for the effective stress range is given in Equation 5 (refer to results section of Task 3).

Vibrations associated with the bending of ancillary structures are believed to be primarily axial or a combination of axial, transverse, and angular vibration. Previous research suggests that severe axial vibrations over a long period might reduce the preload in anchor rods by 30-40% (Bickford, 2008). Analytical research shows that low axial vibrations on connections with high preload lead to no significant change in clamping force (Basava and Hess, 1998). Moreover, high axial vibrations with low preloads result in first loosening and then subsequent tightening of the connection (Basava and Hess, 1998).

Test 1

The summary of vibration testing results is shown in Table 18. The pole in the first test was vibrated at a stress range of 1-3 ksi for 350,000 cycles. The pretension in the rods was 30 ksi

(0.4*F_u). A four percent stress drop was observed, and the majority of the loss in pretension was in the first few hours of vibration testing. Change in nut rotations was minimal during the course of the testing. After 350,000 cycles, a weld fatigue crack was observed at the gusseted box connection for the mast arm, as mentioned previously.

Table 18. Summary of vibration testing results

Test Number	Configuration	Effective Stress Range (ksi)	Number of Cycles (millions)	Average Pretension in Rod (ksi)	Percentage loss in Pretension (%)	Maximum Change in Nut Rotations (°)
1	with mast arm	1-3	0.35	29	4	1
Weld fatigue crack at mast arm to pole connection						
2	without mast arm	2	1.01	32.5	3.63	1.8
3		2-4	0.34	33	4.16	< 1
Weld fatigue crack at base plate to pole connection. Poles switched.						
4	without mast arm	5.5	1.01	12.75	20	1.1
5		6	1.57	11.22	25.8	1
Weld fatigue crack at base plate to pole connection. Poles switched.						
6	without mast arm	5.5	10.15	8.14	NA	1.5
7		6	0.00048	Hand-tight	100	Loose
8		4	2.25	3	100	4.5
9		3	2.23	2	100	2
10		3.4	1.31	4	100	3.3
11		5.2	5.06	5.5	52.4	0.14
12		4.4	2.67	2	73.5	1.42
13		4.8	3.46	3	68.2	4.8
14		4.8	3.5	4	81	3.28
15		5.1	20.23	5	56.4	NA

Tests 2-6

Subsequent tests involved vibrating the straight pole in the fundamental mode. The vibration stress range was increased while the pretension in the rod was simultaneously decreased. During tests 2 and 3, the pole was vibrated at the same parameters as test 1 but for a higher number of cycles (1 million). At the end of test 3, there was a fatigue crack observed at the root of the weld connecting the base plate and pole. After this, the pole was removed and an identical undamaged pole placed in the fixture. In tests 4 and 5, the pretension in the rods was reduced to approximately 12 ksi, which is close to the appropriate snug tight stress (see Table 18). The vibration stress range was increased to 5 ksi and 6 ksi, respectively, which is close to the maximum significant stress range observed during field monitoring. The top anchor rod in tests 4 and 5 experienced a pretension drop of 20% and 26%, respectively. The majority of the loss in pretension was during the initial few ten thousand cycles. This initial loss of pretension is believed to be due to material deformation at the thread roots, creep, embedment relaxation, and different thermal expansion. This relaxation would generally occur over a longer period but seemed to happen quickly due to the simulated vibrations. The pretension loss curve for test 4 is shown in Figure 41.

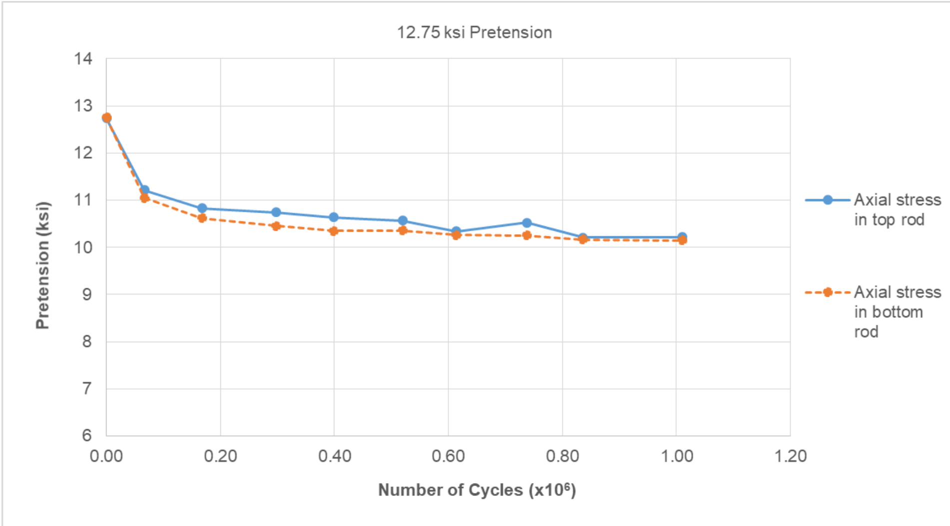


Figure 41. Pretension loss curve for test 4 (12.75 ksi pretension)

There was no significant nut loosening observed even after the vibration cycles were increased to 10 million in test 6 (Table 18). The pretension in the rods was 8.14 ksi and effective vibration stress range was 5.5 ksi. During the vibration testing in test 6, changes in ambient temperature induced stress fluctuations in the bolt strain gages. Since the bolt strain gages were not temperature compensated and no dummy gage was instrumented, the drop in pretension, if any, could not be recorded. However, there was no significant change in nut rotations observed during the test. Subsequent vibration tests involved the use of a dummy bolt strain gage to account for any thermal-induced stress fluctuations.

Tests 7-11

After the first six tests, the decision was made to reduce the pretension to 5 ksi and less for further tests to determine if loosening would potentially occur at lower pretension values. Test 7 involved vibration testing of hand-tightened anchor rods. There was complete loss of pretension and loosening in the top nut after 480 cycles of 6 ksi effective stress range (Table 18). Further vibration testing of anchor rods tightened at a low snug tight value of 3 ksi was conducted in test 8. A steady but slow drop in pretension of the top anchor rod was observed over five days. After 2.25 million vibratory cycles, a complete loss of pretension and loosening in the top nut (4.5˚) was observed. The pretension vs. number of cycles for Test 8 is shown in Figure 42.

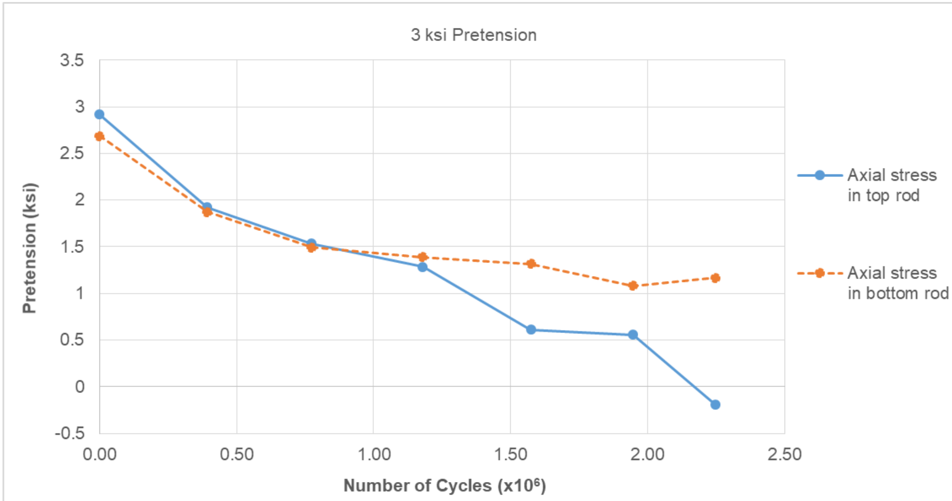


Figure 42. Pretension loss curve for test 8 (3 ksi initial pretension)

Tests 9 and 10 involved vibration testing of the pole with 2 ksi and 4 ksi initial anchor rod pretension, respectively. There was complete loss of pretension observed in both of the tests (Table 18). The number of vibratory cycles to loosening were 2.23 million and 1.31 million for test 9 and test 10, respectively. After these tests, the pretension in the anchor rods was further increased to approximately 5 ksi for vibration test 11. The aim was to determine the pretension threshold at which loosening due to 4-5 ksi of vibration stress range occurs. However, there was only 52% pretension loss observed after 5 million cycles of 5 ksi stress range. The majority of loss in pretension was during the first one million cycles due to initial relaxation. There was minimal change in nut rotations and pretension beyond the first million cycles during the testing. Therefore, vibration testing was stopped at 5 million cycles, taking into account the field monitoring data, which suggested that the field instrumented traffic signal should experience about 5 million cycles of 4 ksi stress range in a span of four years. Four years is also the base inspection frequency for the traffic signal structures as per the VDOT Traffic Ancillary Structures Inventory & Inspection Manual (VDOT, 2014). From the test results, it can be concluded that 5 ksi is approximately the pretension threshold for loosening of anchor nuts at 4-5 ksi stress range. Therefore, anchor rods initially tightened to the minimum installation pretension along with verification using torque after tightening and regular base inspections every four years for the traffic signals can reduce the loosening of nuts over time. Loss in pretension over the course of test 11 can be seen in Figure 43.

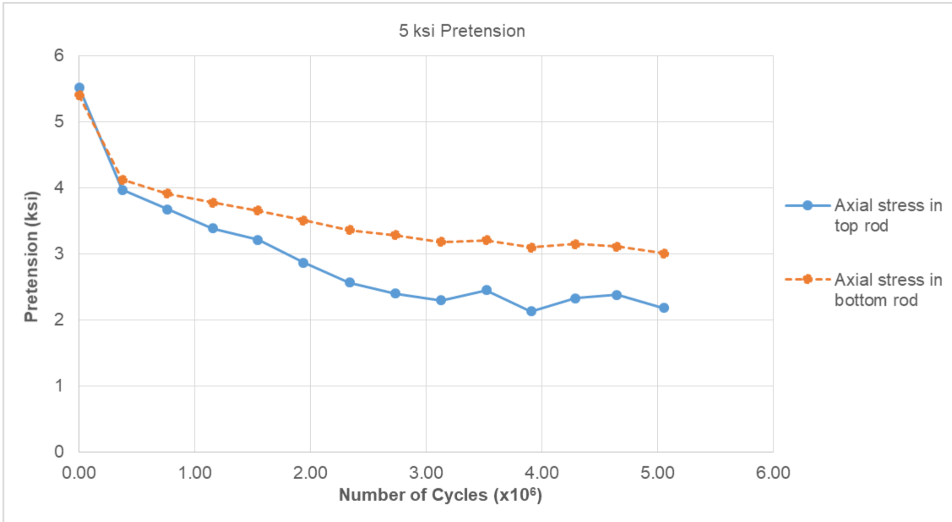


Figure 43. Pretension loss curve for test 11 (5 ksi initial pretension)

Tests 12-15

Tests 12 to 14 involved repetition of vibration testing at 2, 3, and 4 ksi initial pretension, respectively. The aim of the repetition was to find out the variation in the number of vibration loosening cycles at each of these pretension levels. However, little variation was found, and most of the loosening at 2-4 ksi levels of pretension happened within 2.5-3.5 million cycles similar to the tests 8-10. The anchor rods in tests 12-14 did not completely lose pretension but the loss was approximately 70%. The pretension loss curve for test 13, which was the repetition for 3 ksi pretension, is shown in Figure 44. During this test, the pole was going in and out of resonance after 3.5 million cycles and, therefore, the test was stopped when there was approximately 33% pretension left in the anchor rods. The anchor nuts were almost loose enough to remove by hand and were backed off using minimal wrench torque. The change in nut rotation curve for test 13 is shown in Figure 45.

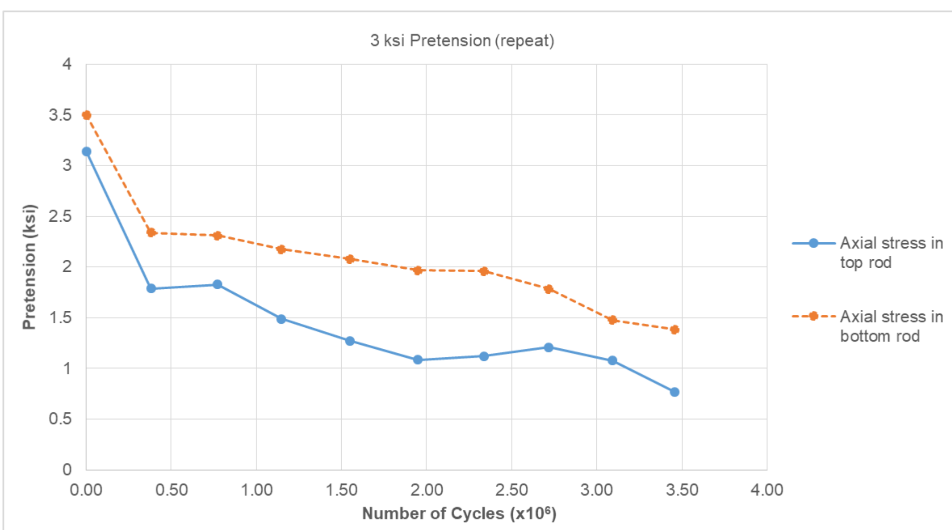


Figure 44. Pretension loss curve for test 13 (3 ksi initial pretension repeat)

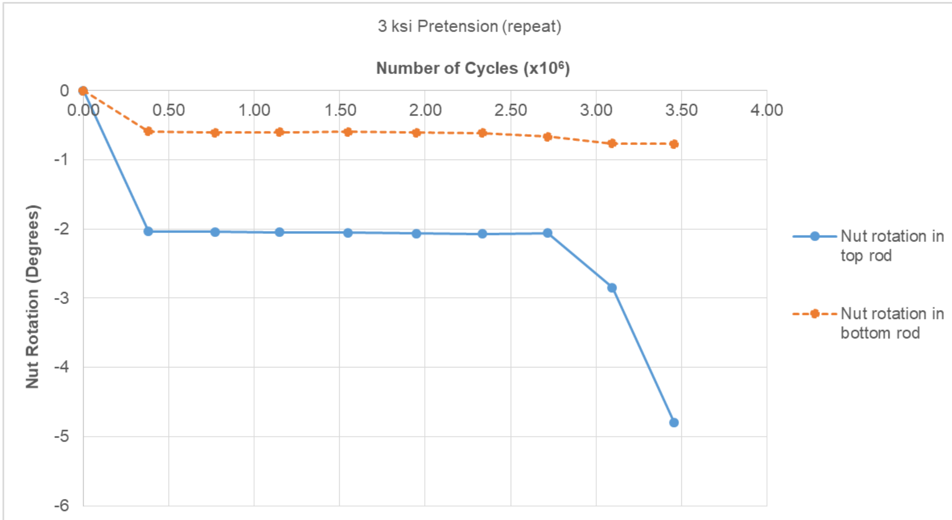


Figure 45. Curve for change in nut rotation during test 13 (3 ksi initial pretension repeat)

In Test 15, the anchor rods were vibrated at 5 ksi initial pretension for a longer period of time. The anchor rods experienced a partial loss in pretension (~56%) after 20 million cycles of 5 ksi vibration stress range. The test results verified that 5 ksi initial pretension is the threshold below which anchor nut loosening begins to happen. 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.

The overall behavior of pretension and nut rotation in the anchor rods of test 13 due to vibrations was divided into 3 stages. The first stage involved relatively quick nut rotation accompanied by initial relaxation after tightening. The second stage involved steady loss of pretension and relatively constant nut rotation. The third stage was characterized by rapid backing of the nut along with slightly increased loss in pretension. This overall loosening behavior is evident from the loosening curves in Figure 44 and Figure 45.

Fully pretensioned anchor rods did not experience any nut loosening, however, anchor nut loosening was observed at lower levels of pretension (i.e., less than 5 ksi). The minimum installation pretension specified in the current tightening specifications was shown to be much greater than the pretension threshold of 5 ksi found out for anchor nut loosening portion of this study. This suggests that there is no need for a second top nut or jam nut over the first top nut in a double nut moment connection provided the top and bottom nuts are tightened to the minimum installation pretension.

Observations and Findings

1. The pretension threshold for vibration loosening on ancillary structures was found to be approximately 5 ksi. It was observed that double-nut moment connections with pretension greater than 5 ksi did not become completely loose when vibrated with 4-5 ksi of pretension for over twenty million cycles.
2. It was found that vibration loosening of anchor nuts in ancillary structures only appears to happen at lower levels of pretension less than 5 ksi. In six tests, two each

involving vibration testing at 2, 3, and 4 ksi, the nut became loose within 1.5-3.5 million cycles.
3. It was concluded that a double nut or jam nut over the top nut in a double nut moment connection is not required.
4. It was concluded that improper tightening (tightening at very low levels of pretension) along with wind-induced vibrations can lead to loosening of anchor nuts on ancillary structures.
5. Weld cracks at the root of stiffened box connections and the base plates were observed during the testing. There were no fatigue cracks observed in the anchor rods as the stress range was below the threshold of 7 ksi during all the tests.
6. The majority of initial loss in pretension during the tests was likely due to material deformation, embedment relaxation, and differential thermal expansion. It is believed that this loss in pretension was accelerated due to the effect of vibrations.

Task 5: Small-scale Vibration Testing

Experimental Test Results

A total of five tests were conducted on a component scale to validate the results of the large-scale testing. A double-nut moment connection consisting of a single anchor rod was vibrated axially in a fatigue-rated universal testing machine. Based on the results of the large-scale testing, anchor rods at critical pretension levels (2, 3, 4 and 5 ksi) were tested. The loss in pretension was recorded using the bolt strain gages similar to the large-scale testing. The vibrational frequency was set at 4 Hz for the first five tests and at 4.7 Hz for the last test. The summary of vibration results is shown in Table 19.

Table 19. 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

Tests 1-5

Tests 1 and 2 involved vibration testing of the connection at the initial pretension level of 3 and 2 ksi, respectively. There was approximately 88% loss of pretension observed in both tests after 2 million cycles. The effective stress range was 3.5 ksi. The vibrational loosening curves for test 2 are shown in Figure 46. After tests 1 and 2, the connection pretension was set at 4 ksi. There was no significant change in nut rotation observed during test 3. The majority of the 51% loss in pretension occurred during the initial few thousand vibration cycles (see Figure 47). Tests

4 and 5 were repetitions of test 2 and 1, respectively; however, anchor rods in both the tests did not become completely loose. There was still approximately 0.6 ksi and 1.5 ksi pretension left in the anchor rod after completion of tests 4 and 5, respectively. Anchor rod vibrations were also conducted at the 5 ksi pretension threshold identified from large-scale testing. However, the anchor rod experienced a partial loss in pretension (~61%) after 20 million cycles of 5 ksi vibration stress range.

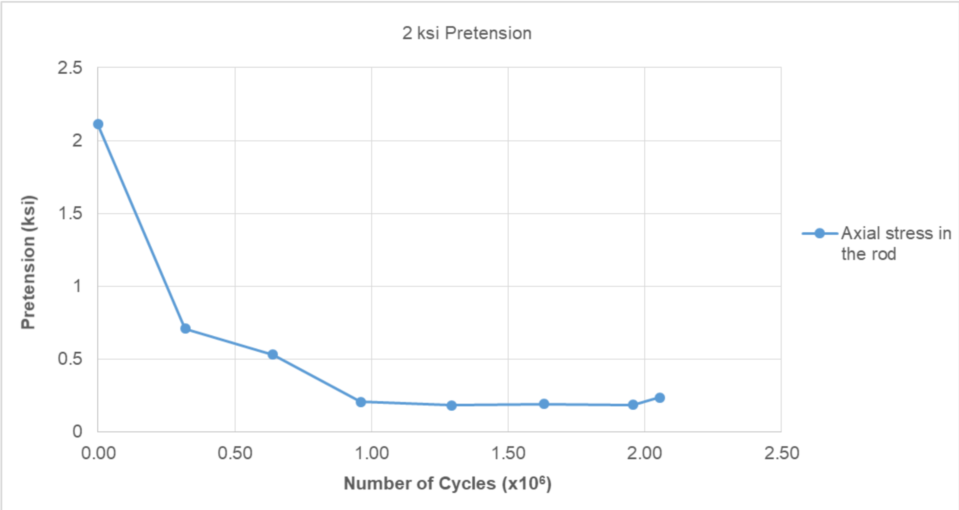


Figure 46. Vibrational loosening curve for test 2 (2 ksi pretension)

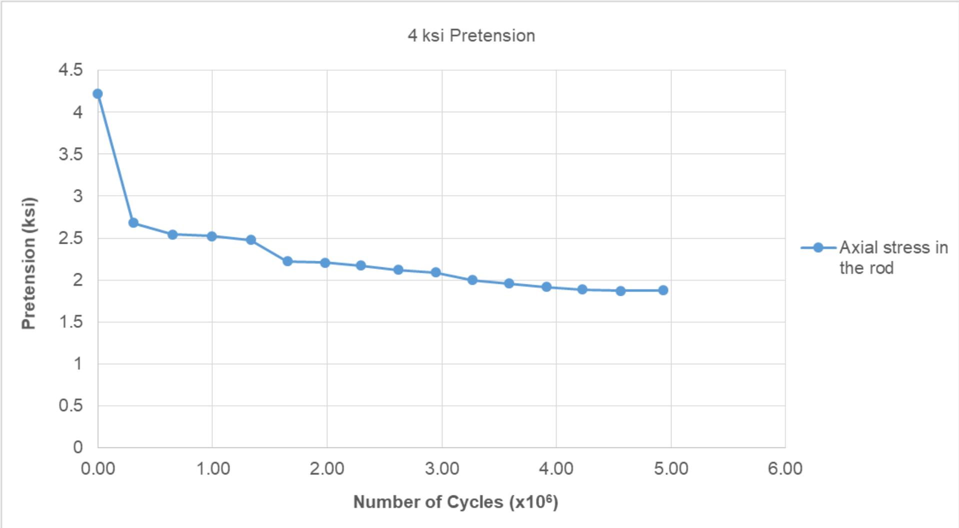


Figure 47. Vibrational loosening curve for test 3 (4 ksi pretension)

Comparison of Large-Scale and Small-Scale Testing

Test 3 results were found to be similar to the results for the 5 ksi pretension test (test 11) in large-scale testing (see Figure 43 and Figure 47). Therefore, the pretension threshold in the small-scale testing was found to be 4 ksi as compared to 5 ksi in the large-scale testing. The loosening of anchor nuts at 4 ksi pretension in the large-scale testing but not in the small-scale testing could be a result of secondary contribution of other types of vibrations, like transverse and rotational vibrations during the full-scale testing. The total number of cycles to loosening at the same levels of pretension were found to be very close for both large-scale and small-scale tests (see Table 18 and Table 19). Therefore, it could be concluded that small-scale testing involving axial vibrations was a close approximation of the large-scale testing. A comparison of loss of pretension curves at 3 ksi pretension for both large-scale and small-scale testing is shown in Figure 48. The results of both tests produced the same general shape of the loosening; the only difference is that large-scale testing involved gradual decrease in pretension as compared to the small-scale testing (see Figure 48).

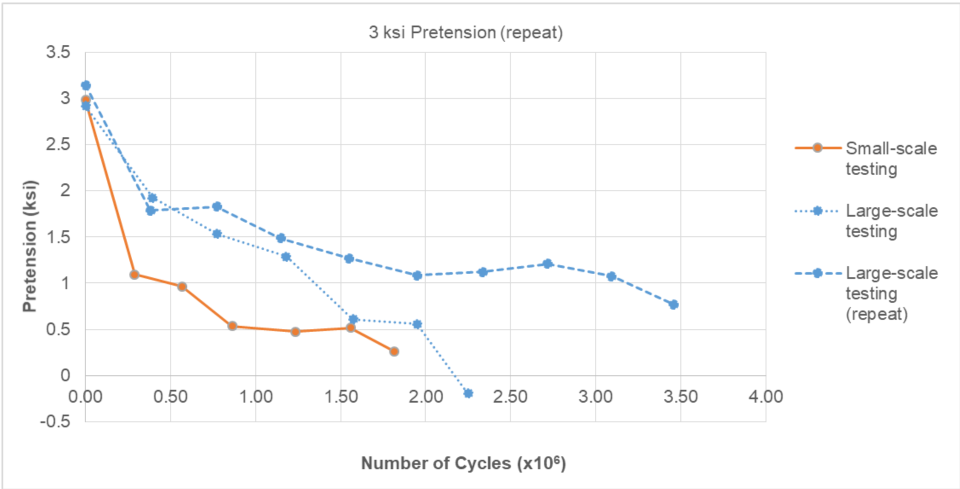
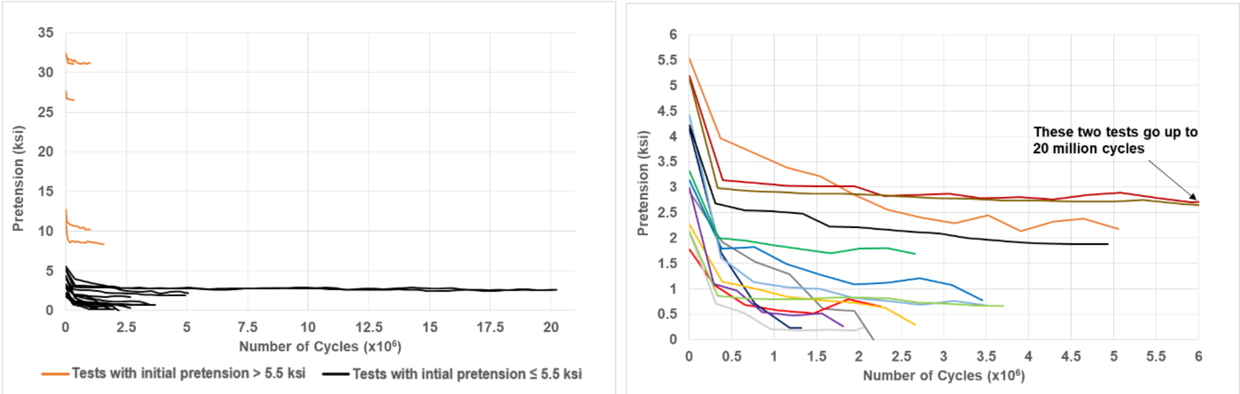


Figure 48. Comparison of pretension loosening curves at 3 ksi initial pretension

A combined pretension loosening graph for all the large-scale and small-scale vibration tests is shown in Figure 49a. It can be seen from the combined loosening graph that all the tests with anchor rod pretension less than or equal to 5.5 ksi experienced significant loss in initial pretension of at least 51%. The pretension loosening behavior for all the tests with initial pretension less than or equal to the 5.5 ksi which is close to the observed pretension threshold of 5 ksi for loosening is shown in Figure 49b.



(a) (b)

Figure 49. Initial pretension vs. number of cycles for (a) all vibration tests and (b) tests with initial pretension less than or equal to 5.5 ksi

Observations and Findings

1. There was no significant loosening observed at 4 ksi initial pretension. Therefore, the pretension threshold was found to be 4 ksi for the small-scale testing results. This was only 1 ksi less in comparison to the 5 ksi as determined from the large-scale testing results.
2. The number of vibration cycles until loosening were found to be similar for both small- and large-scale tests. Hence, small-scale test results provided a good validation for the large-scale testing results.
3. The overall shape of the loosening curve remained the same, but small-scale test results showed faster initial decrease in pretension as compared to the large-scale test results.

Task 6: Evaluation of Thread Fabrication Tolerance

Anchor Rods

The thread parameters for galvanized anchor rods and nuts were measured using the procedure as detailed in the methodology section of Task 6. The results were compared with the allowable tolerances as specified in ASTM standards (ASTM, 2015a; ASTM, 2015b). The allowable tolerances are shown in Table 2 and Table 3. The average readings of the thread parameters for the anchor rods from each supplier and their variation from the required tolerances are shown in Table 20, Table 21, and Table 22. Both the major diameter and the pitch diameter for all five diameters and three suppliers were found to be less than the maximum allowable tolerances, which is seen from the negative percentage variation shown in Table 20, Table 21, and Table 22. Flank angle variation was also negligible with a variation of +/- 0.25˚.

Table 20. Measured thread parameters for anchor rods from Supplier 1

ASTM F1554 Galvanized Anchor Rods (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 (%)
0.75	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
1.25	1.0618	30.00	1.2350	-2.89	1.1404	-3.28
1.5	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 21. Measured thread parameters for anchor rods from Supplier 2

ASTM F1554 Galvanized Anchor Rods (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 (%)
0.75	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
1.25	1.0703	29.80	1.2435	-2.23	1.1540	-2.12
1.5	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 22. Measured thread parameters for anchor rods from Supplier 3

ASTM F1554 Galvanized Anchor Rods (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 (%)
0.75	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
1.25	1.0649	30.10	1.2460	-2.03	1.1539	-2.13
1.5	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 in the major diameter, minor diameter, and pitch diameter for of all the anchor nuts from the three suppliers are shown in Table 23, Table 24, and Table 25. The minor diameter measurements for the anchor nuts were within the allowable tolerances except the 0.75 in anchor nuts from Supplier 3. Pitch diameter measurements for the anchor nut specimens were found to be within the allowed tolerance for only 4 out of the 15 diameters measured. Ten out of the 15 specimens exceeded the allowable tolerances. The maximum variation was 1.26% for 1.25 in anchor nut from Supplier 3 (see Table 25).

Table 23. Measured thread parameters for anchor nuts from Supplier 1

ASTM A563 Galvanized Anchor Nuts (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 (%)
0.75	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	
1.25	30.15	1.3087	2.73	1.2048	1.18	1.1355	
1.5	30.18	1.5369	0.65	1.4242	Within range	1.3532	
2	30.07	2.0881	1.86	1.9281	0.52	1.8242	

Table 24. Measured thread parameters for anchor nuts from Supplier 2

ASTM A563 Galvanized Anchor Nuts (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 (%)
0.75	29.83	0.8014	4.08	0.7101	Within range	0.6623	Within range
1	30.15	1.0496	2.50	0.9563	0.49	0.9000	
1.25	29.93	1.2977	1.86	1.1960	0.43	1.1323	
1.5	30.13	1.5539	1.76	1.4303	0.08	1.3570	
2	30.13	2.0732	1.13	1.9120	Within range	1.8160	

Table 25. Measured thread parameters for anchor nuts from Supplier 3

ASTM A563 Galvanized Anchor Nuts (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 (%)
0.75	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
1.25	29.87	1.3047	2.41	1.2058	1.26	1.1393	
1.5	30.05	1.5693	2.77	1.4381	0.63	1.3560	
2	30.08	2.0515	0.07	1.9117	Within range	1.8100	

The major diameter measurements for all the anchor nut specimens from the three suppliers were above the minimum allowable tolerance (refer to Table 23, Table 24, and Table 25). There were no specified maximum tolerance limits on the major diameter of anchor nuts. The major diameter measurement of 0.75 in anchor nut from supplier 2 was found to have the maximum variation (4.08%) from the minimum allowable tolerance. The flank angle measurements were close to 30˚ and varied in the range of 29.8˚-30.18˚.

The major diameter measurements for the anchor rods and anchor nuts satisfied the allowable tolerance limits (maximum allowance for anchor rods and minimum allowance for anchor nuts). However, the measured major diameters of the anchor nut specimens were found to be 1-4% larger than the minimum allowable tolerances and the major diameter of the anchor rod specimens were found to be 2-3% smaller than the maximum allowable tolerances. These tolerances indicate that there are gaps between the mating threads of anchor rods and nuts. These gaps are small and are believed to have negligible impact on nut loosening.

Lastly, it was also observed during testing that inadequate lighting led to improper edge detection and poor image quality. A completely dark room and appropriate directional lighting aided in getting good quality images.

Observations and Findings

1. The major diameter of all the anchor rod specimens and anchor nut specimens satisfied the allowable tolerance limits (maximum tolerance for anchor rods and minimum tolerance for anchor nuts).
2. The major diameter measurements of anchor rods and anchor nuts indicate that there are small gaps between the mating threads. However, these gaps are believed to have negligible impact on nut loosening.
3. The pitch diameter for 10 out of the 15 anchor nut specimens were out-of-tolerance. However, small variations in the pitch diameter measurements were not considered detrimental to nut loosening.

Task 7: Tightening Procedures for Anchor Nuts on Transformer Base (T-base) Poles

As discussed in the Methods section, each of the four rods were tightened five times in total. First, unlubricated rods were tightened using each of the two tightening techniques: access hole and extension. Then, the rods were lubricated and tightened using the same two techniques. Each lubricated anchor rod was tightened beyond the yield strength during the last tightening sequence.

Yield and Tensile Strength

Grade 55 anchor rods were used for the tightening study. The maximum reported 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 Methods section, the anchor nuts on the T-base were tightened using two techniques. The first technique involved using a 3 in 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 in 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-tightening pattern, as shown in Figure 50. 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.

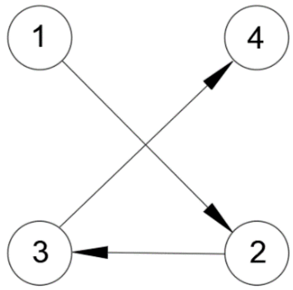


Figure 50. Star-tightening pattern for tightening of 4 anchor rods

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 51. 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, lubrication facilitates the tightening process and makes it easier to achieve desired pretension at relatively lower levels of torque.

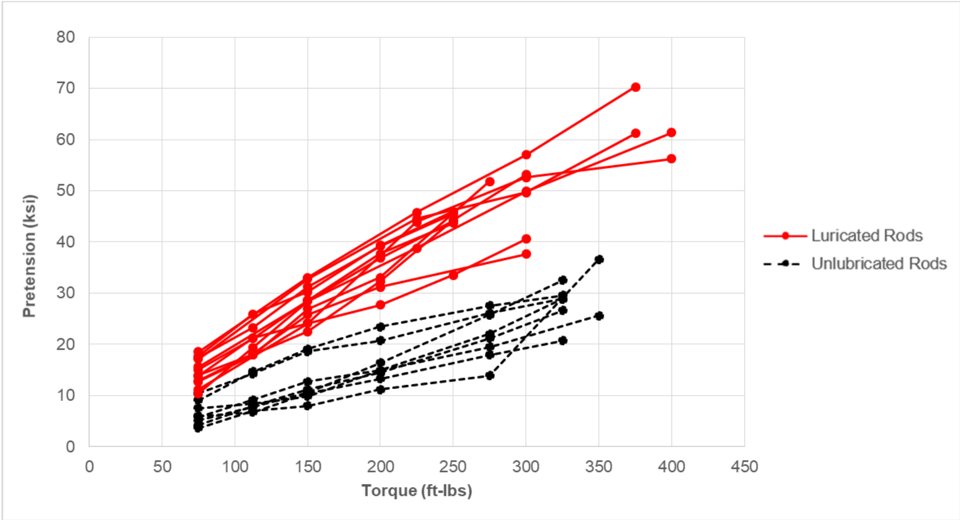


Figure 51. Comparison of pretension vs. torque relationship between lubricated and unlubricated rods

Lubricated Rods

Pretension vs. Torque

The pretension vs. torque relationship for the lubricated anchor rods is shown in Figure 52. All four of the anchor rods behaved similarly. 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 52). 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). 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.

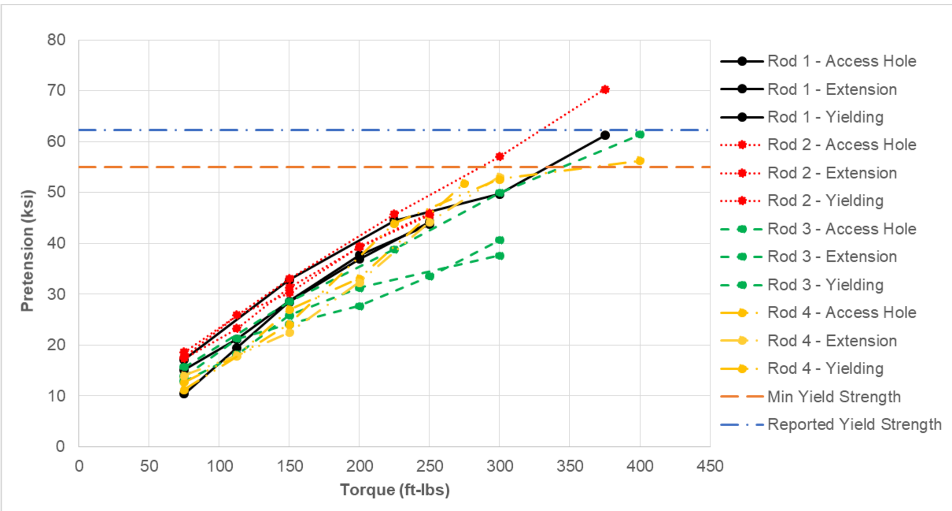


Figure 52. Pretension vs. torque curve for lubricated rods

Pretension vs. Nut Rotation

The pretension vs. nut rotation curves for all of the tested rods are shown in Figure 53. 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 53). 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˚.

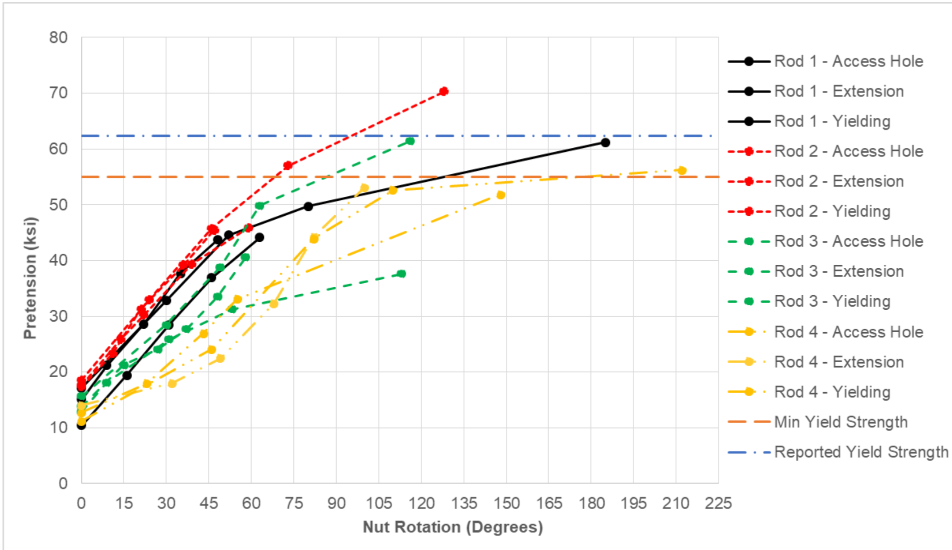


Figure 53. Pretension vs. nut rotation curve for lubricated rods

Observations and Findings

1. It is very tedious and time consuming to measure nut rotations inside the T-base. Observations during testing showed that torque, rather than turn-of-the nut, is a much easier tightening method when tightening single-nut connections on T-bases.
2. If the turn-of-the-nut tightening procedure 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-lb of torque produces only 25-35 ksi of pretension in single-nut connections on T-bases. A larger torque value (250 ft-lb) would allow for proper tightening of lubricated grade 55 anchor rods on T-bases and single-nut connections without yielding the rod.
4. The testing results indicated that lubrication facilitates the ease of tightening. Unlubricated rods during the testing required large amount of torque for tightening as compared to the lubricated rods.
5. Tightening of anchor nuts inside the T-base is challenging. 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. It was also observed that incrementally tightening the anchor rods in star-tightening pattern leads to better distribution of rod stresses.

Task 8: Evaluation of Inspection Methods

There are several methods to determine pretension in a bolted connection. Some of the common methods include torque verification, bolt strain gages, ultrasonic stress measurement, elongation measurement using micrometers, digital image correlation, donut load cells/washers, seismic testing (hammer vibration analysis), and magnetic transducers (Phares et al., 2016). The torque verification technique is based on a relationship between the applied torque and pretension in the bolted connection. This technique is inconsistent because the amount of applied torque depends on friction and lubrication between the anchor rods and nut. Most other methods are not feasible for post-inspection of already tightened bolted connections. Bolt strain gages require predrilled holes for their placement. Through-hole load cells require their use as washers in the connections. Digital image correlation (DIC) produces accurate results but is a relatively new and expensive technique. Similar to the previously mentioned techniques, DIC compares relative rotation and is therefore required to be used throughout the tightening process.

The use of ultrasonic techniques is gaining popularity because of its portable nature and non-dependence on lubrication and friction (Walaszek et al., 2016). In general, Ultrasonic Testing (UT) involves the use of high-frequency sound waves to detect any imperfections, cracks, or change in material properties. Ultrasonic bolt stress measurement requires either using a piezoelectric transducer or an electromagnetic acoustic transducer (EMAT). The bolt tightening leads to the formation of a stress field inside the bolt (Phares et al., 2016). The stress field alters the velocity of the ultrasonic waves transmitted through the tightened bolt and creates a time delay for the wave to return back to the transducer (Nassar and Veeram, 2006; Hartmann, 2016). The time delay and the change in velocity are used to calculate the pretension in the bolt.

When using piezoelectric transducers, the transducer needs to be in contact with the bolt head or anchor rod end. It generally requires a couplant (liquid medium) to transmit ultrasonic waves inside the bolt or anchor rod. Piezoelectric transducers only transmit longitudinal waves, therefore, these transducers require a differential measurement of ultrasonic wave travel time. The difference in travel time between the unstressed and stressed bolt/rod is used to measure the bolt/rod elongation and, hence, the pretension in the bolt/rod. Therefore, initial measurements are required to be conducted on the bolt/rod if in-situ piezoelectric transducers are to be considered. This dependence is overcome with the use of EMAT. EMAT transmits both longitudinal and shear waves, which eliminates the need for measurements in the unstressed state. The electromagnetic acoustic interaction also eliminates the need for a coupling. Hence, EMAT offers the option of non-contact measurements and can also be used on already tightened bolted connections (Ding et al., 2014; Walaszek et al., 2016).

The differential measurement of the stress using ultrasonic waves produces reliable results and is commonly used across industries (Walaszek et al., 2016). On the other hand, the bi-wave method using the EMAT is still in the research stages. The ratio of velocities or time of flight between the waves has been found to have a linear relationship with the pretension in the bolted connection (Ding et al., 2014). The inventory of ancillary structures is very large in the state of Virginia with different types of foundation connections, size, grade, and length of anchor rods. VDOT started formally inspecting sign structures and high-mast light towers in 1997 and later added other structures like luminaires and traffic signals to the inspection program around 2006. Due to the large inventory of existing ancillary structures, the transportation industry is in need of a technique that can measure pretension in situations where bolted connections are already tightened. The new technology is rolling out in the market and there are companies adopting a bi-wave method and EMAT for bolt tension measurement; however, the technique is still in its early stages and is relatively expensive. Further research on ultrasonic bolt stress measurement using both the transducers is still required. The technology is promising and could be used in the future to successfully measure axial stress in the bolted connections.

Task 9: Snug-Tight Study

1 in Anchor Rod

A total of 19 students/workers participated in tightening a 1 in anchor rod on a 1 in thick base plate in a double-nut moment connection. An adjustable ratchet with variable lengths of 12 in, 16 in, and 20 in was used for tightening. Fifty seven data points were recorded for axial stress in the rod due to snug-tightening.

Effect of Wrench Length and Applied Force

The variation in the snug-tight stress is shown graphically using a whisker chart in Figure 54. The overall variation in stress ranged from 8.5 ksi to 63 ksi, which is indicative of the large effect of personnel strength that results from interpretation of the snug-tightening definition in current specifications. It can be seen in Figure 54 that the variation (left extreme to right extreme) in stress increased with increase in wrench length. The median (intersection of grey and yellow shaded area) also increased with the increase in wrench length. The increased wrench length provided extra leverage for the participant to snug-tighten the connection. The grade 55 rod yielded when an adjustable wrench length of 20 in was used. The range of axial stress in the rod was 15% to 79% of F_y (55 ksi) when a 12 in wrench length was used. The recommended snug-tight pretension of 20%-30% of final pretension (9 ksi to 13.5 ksi) given in the NCHRP 469 report and FHWA specifications is also shown with a hatched area in Figure 54. A 12 in wrench length was found to be better than the other two lengths considering that there was no yielding and a relatively smaller variation associated with the tightening.

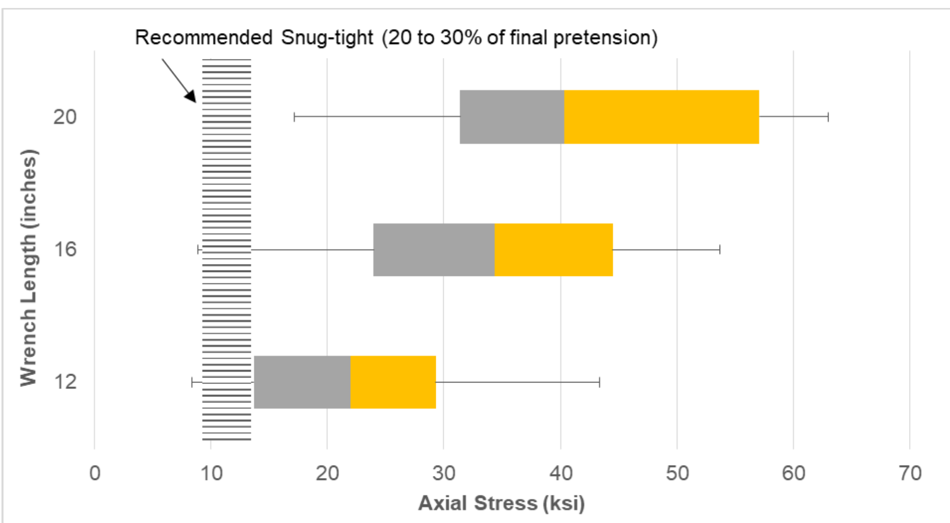


Figure 54. Axial stress distribution for snug-tight pretension in a 1 in anchor rod

2 in Anchor Rod

Sixteen students/workers participated in tightening a 2 in anchor rod on a 2 in thick base plate. An adjustable ratchet with variable lengths of 24 in, 32 in, and 40 in was used for tightening. The variation in the snug-tight stress is shown graphically using a whisker chart in

Figure 55. The overall variation (4-21 ksi) was significantly smaller in the 2 in rod as compared to the 1 in rod. No yielding of the rod was observed. A larger cross-section of the rod made it difficult to tighten the rod. As seen with the 1 in rod, the median and the range of stress increased with the increase in the wrench length. The stress ranged from 7.5% to 25% of F_y (55 ksi) for the 24 in wrench. The recommended snug-tight pretension of 20%-30% of final pretension (9 ksi to 13.5 ksi) given in the NCHRP 469 report and FHWA specifications is also shown with a hatched area in Figure 55. The relatively smaller variation makes the 24 in wrench the better choice for snug-tightening a 2 in anchor rod. This conclusion is also consistent with the use of 18 to 24 in long adjustable wrench for snug-tightening during the tightening study performed in Task 2.

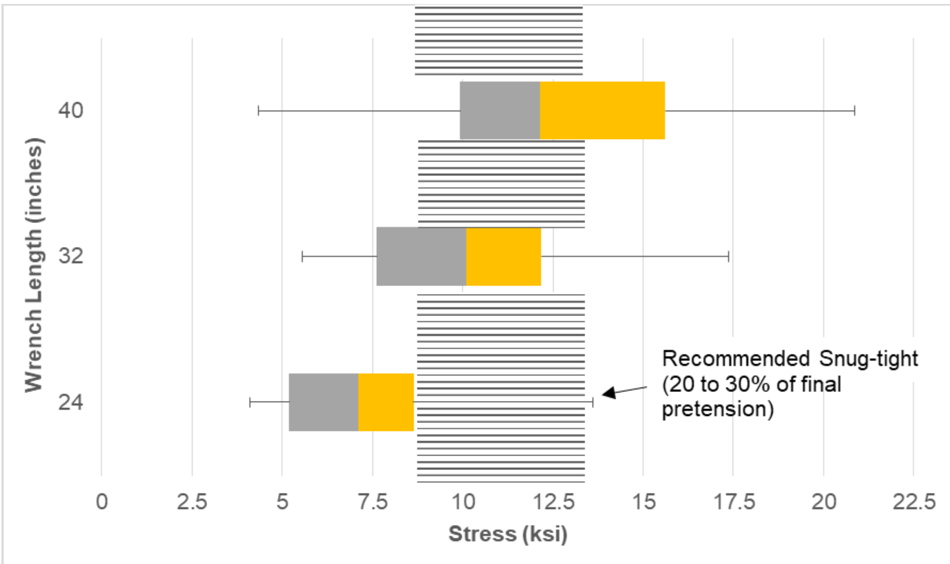


Figure 55. Axial stress distribution for snug-tight pretension in a 2 in anchor rod

Observations and Findings

1. A 12 in long wrench and a 24 in long wrench were good choices for snug-tightening 1 in and 2 in anchor rods, respectively. These wrench lengths will neither lead to under-tightening nor yielding of the rods.
2. The 2 in anchor rod was more difficult to tighten compared to the 1 in anchor rod and, hence, there was a smaller variation of stress in the 2 in rod. Due to the larger variation of stress, care should be taken to not overtighten or yield anchor rods with diameters less than or equal to 1 in.
3. Snug-tight pretension in 1 in anchor rods and most of the 2 in anchor rod tightening trials was found to be greater than 5 ksi, the pretension threshold below which loosening of anchor nuts occur.
4. Increasing the wrench length provides more leverage, leading to a higher snug-tight stress.

CONCLUSIONS

- *The current tightening procedures for double-nut moment connections contain some discrepancies. Some of the recommended nut rotations for turn-of-the-nut method are not accurate and can lead to under-tightening or over-tightening of the anchor rods.* Based on the testing conducted in this project, proposed required nut rotations for grade 36 and 55 anchor rods are provided in the Recommendations and Appendix of this report.

- *Similar to the grade 36 and 55 ksi anchor rods, the current AASHTO turn-of-the-nut tightening procedures for grade 105 anchor rods were also found to have discrepancies which could lead to under- or over-tightening. Observed nut rotations required to produce sufficient pretension were noted within the report, however, these values were not included in the Recommendations because of the VDOT preference to use a larger quantity of grade 55 anchor rods instead of smaller quantity of grade 105 anchor rods.*

- *Snug-tight pretension is highly variable. The resulting pretension depends on various factors such as lubrication, personnel strength, and wrench length. 12 in and 24 in long wrench were tested for snug-tightening on grade 55, 1 in and 2 in diameter anchor rods as part of snug-tight study in this project. The use of appropriate wrench length for a specific diameter of an anchor rod can reduce the chances of yielding the anchor rod during snug-tightening or subsequent pretensioning.*

- *Tightening single-nut connections inside a T-base is challenging. The use of deep sockets, long extensions used from the top bolt holes, and proper lubrication can help facilitate the tightening process.*

- *The current manufacturer recommended installation torque of 150 ft-lbs for tightening single-nut connections on T-bases is inadequate. Testing found that an installation torque value of 250 ft-lbs ensured proper tightening. However, the manufacturer recommended installation torque of 150 ft-lbs is based on crash testing of the T-base connection and can only be revised after further research on the tightening torque requirements for crash testing. Therefore, a new tightening torque value has not been included in the recommendations.*

- *The fundamental mode of the mast-arm each in the in-plane and out-of-plane direction were the dominant modes for the traffic signal and luminaire during field monitoring.*

- *Wind-induced vibrations can loosen improperly tightened anchor nuts on ancillary structures over time. It was concluded from the test results that it only takes about 2-4 million vibration cycles to loosen a double-nut moment connection if the anchor rod has low levels of initial pretension (less than 5 ksi).*

- *A jam nut or second top nut over the first top nut in a double-nut moment connection is not required provided the anchor rod is tightened to the minimum installation pretension. However, more field evidence suggestive of reduction in cases of anchor nut loosening as a result of proper rod tightening is required before revisions involving the removal of jam nut or second top nut in the tightening specifications can be made.*

- *Evidence suggests that there are gaps between the mating threads of galvanized anchor rods and anchor nuts. However, it is believed that gaps are small and would have a negligible impact on nut loosening.*

- *Proper tightening of the anchor rods to the recommended nut rotations (minimum installation pretension) along with torque verification after tightening and regular inspections would reduce the cases of anchor nut loosening over time.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division and Traffic Engineering Division should revise the VDOT Road and Bridge Specifications for the following recommended nut rotations for double-nut moment connections: for anchor rods less than 1 in in diameter, grade 36 rods should be tightened to 60°, and grade 55 rods should be tightened to 75°; for anchor rods 1 in in diameter and greater, grade 36 rods should be tightened to 45°, and grade 55 rods should be tightened to 60°.* These modified tightening specifications will ensure proper tightening of these connections without any under-tightening or yielding of the rods.

2. *VDOT's Structure and Bridge Division and Traffic Engineering Division should revise the VDOT Road and Bridge Specifications for inclusion of an additional section specifying the proper tightening procedure for single-nut connections.* These proposed tightening procedures are similar to those already found in the VDOT Road and Bridge Specifications for double nut connections, with the incorporation of a specified torque instead of turn-of-the-nut for ease of tightening especially inside transformer bases and a statement for ensuring that all threads of the rod, nuts, and bearing surfaces are free of debris that could lead to improper tightening.

3. *VDOT's Structure and Bridge Division and Traffic Engineering Division should revise the VDOT Road and Bridge Specifications for inclusion of a table specifying the recommended wrench sizes during snug-tightening depending on the diameter and grade of the anchor rod.* In general, a 12 in wrench should be used for snug-tightening 1 in diameter anchor rods of both grade 36 and grade 55, and 2 in diameter anchor rods of grade 36. A 24 in wrench should be used for snug-tightening 2 in diameter grade 55 anchor rods.

4. *VDOT's Structure and Bridge Division and Traffic Engineering Division should revise the VDOT Road and Bridge Specifications for inclusion of a statement specifying the time window for application of verification torque after final tightening as 48 hours to 1 week.* This inclusion will ensure verification of minimum pretension in every anchor bolt after completion of final tightening.

5. *VDOT's Structure and Bridge Division* and *Traffic Engineering Division should revise the VDOT Road and Bridge Specifications to specifying the use of deep sockets with long extensions used from the top bolt holes for proper tightening of anchor nuts inside T-bases.*

6. *VDOT's Structure and Bridge Division and Traffic Engineering Division should develop a training program on proper tightening methods of anchor rod installation on ancillary structures.*

IMPLEMENTATION AND BENEFITS

Implementation

Implementation of Recommendations 1-5 will include revisions to the VDOT Road and Bridge Specifications as provided in the Appendix. Once complete, these revisions will be submitted to the FHWA Structures Division for concurrence. Upon their approval by FHWA, the recommended changes will be submitted to the VDOT Construction Division to obtain industry comments and further submitted to FHWA for final concurrence. All of the recommended revisions apply to Section 700 – General, 700.05 – Procedures, (k) Anchor Bolts. Recommendations 1-5 apply only to the initial submission of revisions to FWHA, which will occur within 2 years of publication of this report. The subsequent revisions and approvals required after the initial submission to FHWA can be subject to lengthy delays, which is why they are not included within the 2-year period to complete Recommendations 1-5.

Implementation of Recommendation 6 includes the development of a training program focused on proper installation and tightening of anchor rods and nuts. It is envisioned that this training program will be similar to the high strength bolting course that the VDOT Materials Division provides to engineers, inspectors, contractors, etc. Implementation of Recommendation 6 will occur within 5 years of publication of this report.

Benefits

The benefit of implementing Recommendations 1-5 is that they provide VDOT with a more consistent anchor rod nut tightening procedure for double-nut moment connections, which should aid in preventing cases of improper tightening and nut loosening. The proposed revisions to the tightening specifications in Recommendations 1-5 will also aid VDOT in properly tightening single-nut connections especially inside transformer bases. Overall, the proposed tightening revisions should significantly reduce the number of loose anchor nuts, which will make for safer ancillary structures that require less maintenance.

The benefit of implementing Recommendation 6 is that a training course on proper tightening of anchor nuts will increase the knowledge of the labor force who is responsible for the initial tightening of anchor nuts on ancillary structures. Better informing the labor force about proper tightening methods should reduce cases of improper tightening and consequent loosening of anchor nuts.

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APPENDIX

Development of Nut Tightening Procedures

Recommended changes to VDOT Road and Bridge Specifications 2016

The recommended additions and changes to the tightening procedures for double-nut and single-nut connections are highlighted in red (VDOT 2016a).

Section 700 – General

700.05 – Procedures

(k) Anchor Bolts

Foundations for traffic control device structures (signal poles, overhead sign, lane control, variable message signs, and high-mast lighting structures) shall have a bolt template positioned for the correct orientation of the structure with respect to the structure's location and roadway alignment and to maintain the anchor bolts vertical (plumb) and level during construction.

Bolt and/or anchor nut covers shall not be installed on any traffic control device structures, unless otherwise specified on the plans.

Anchor bolts in double-nut connections shall extend a minimum of 1/4 in. past the second top nut.

The threaded portion of the anchor bolts shall be lubricated with beeswax, the bolt manufacturer's recommended lubricant, or other lubricant as approved by the Engineer to assist in proper tensioning before the structure is installed.

Double-nut connections

Double-nut connections installation procedures shall conform to the following:

1. A minimum of three nuts and two hardened washers shall be provided for each anchor bolt.
2. If anchor bolt(s) are not plumb (vertical), determine if beveled washer(s) may be required prior to erection of the structure. Beveled washers shall be used on top of the leveling nut and/or under the first top nut if any face of the base plate has a slope greater than 1:20 and/or if any nut could not be brought in firm contact with the base plate.
3. Clean and lubricate the exposed threads of all anchor bolts, nuts and all bearing surfaces of ~~all leveling nuts~~ nuts and washers. Ensure that the threads of the rod, nuts, and bearing surfaces of the nuts and washers are free of dirt, concrete, debris, or other contaminants since these can lead to improper tightening. 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. Verify that the nuts can be turned onto the bolts the full length of the threads by hand.
5. Turn the leveling nuts onto the anchor bolts and align the nuts to the required elevation shown on the shop drawings. The maximum distance between the bottom of the leveling nut and the top of the foundation shall be one in. (1”).
6. Place structural hardened washers on top of the leveling nuts (one washer corresponding to each anchor bolt).
7. The post or end frame shall be plumbed or aligned as shown on the shop drawings. The maximum space between the bottom of the base plate and the top of the foundation shall be the diameter of the anchor bolt plus one (1) in. Place structural hardened washers on top of the base plate (one washer corresponding to each anchor bolt), and turn the first of the top nuts onto the anchor bolts.
8. Tighten first 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 ~~12in. long wrench or equivalent.~~ wrench with the recommended length determined from Table VII-1. 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.

Table VII-1 – Wrench Size

Anchor Bolt Diameter, (in.)	**Recommended Wrench Length (in.)**	
	ASTM F1554 Grade 36 (M314)	**ASTM F1554 Grade 55 (M314)**
≤ 1	12	12
> 1 and < 2	12	*
2	12	24
> 2	**	**

*The wrench length for grade 55 anchor bolts (> 1 and < 2) may be set by a linear relationship
**Contact Central Office Structure and Bridge for size of wrench to be used for anchor bolts greater than 2".

9. Tighten bottom leveling nuts to a snug-tight condition in a star pattern.
10. At this point, verify again if beveled washers are necessary using the criteria from step 2. If a beveled washer is required, remove the structure if necessary, add the beveled washer(s) and retighten first top nuts and bottom leveling nuts (in a star pattern) to a snug-tight condition.
11. Mark the reference position of each first top nut in a snug-tight condition with a suitable method on one flat surface of the nut with a corresponding reference mark on the base plate at each bolt before final tightening of the first top nuts. Then rotate the first top nuts incrementally to one half the required nut rotation specified in Table VII-~~1~~2 using a star pattern. Rotate the first top nuts again, using a star pattern, to the full required nut rotation specified in Table VII-~~1~~2. For example, if total rotation from snug tight is 1/6 turn (60º), rotate 30º in each cycle.

Table VII-12 – Nut Rotation

Anchor Bolt Diameter, (in.)	Nut Rotation beyond Snug-Tight	
	ASTM F1554 Grade 36 (M314)	ASTM F1554 Grade 55 (M314)
≤ 1½	1/6 turn (60˚)	1/3 turn (120˚)
> 1½	1/12 turn (30˚)	1/6 turn (60˚)

Nut rotation is relative to anchor bolt. Anchor bolt nut tensioning shall not exceed plus 20º.

Unified Thread Standard (UNC) tensioning is applicable.

Anchor Bolt Diameter, (in.)	Nut Rotation beyond Snug-Tight*	
	ASTM F1554 Grade 36 (M314)	ASTM F1554 Grade 55 (M314)
< 1	60˚	75˚
≥ 1	45˚	60˚

*Nut rotation is relative to anchor bolt. Tolerance for anchor bolt nut tensioning shall be +15º.

*Unified Thread Standard (UNC) tensioning is applicable.

*Minimum target pretension is 50% and 60% of minimum tensile strength of grade 36 and 55, respectively.

The Engineer will not permit the use of lock nuts and/or split washers with anchor bolts.

12. The Contractor shall inspect tightened anchor bolt connections by the use of a calibrated torque wrench in the presence of the Engineer. The torque wrench shall be used to verify that a torque at least equal to the verification torque provided in Table VII-23 has been achieved for every anchor bolt. The torque verification shall be performed between 48 hours to 1 week after tightening to overcome any stress relaxation. A minimum of every other bolt shall be inspected.

Table VII-23 – Torque Verification

Anchor Bolt Diameter, (in.)	Verification Torque	
	ASTM F1554 - Grade 36 (M314)	ASTM F1554 - Grade 55 (M314)
	Tension/Torque kips/ft-lbs	
1	18 / 180	27 / 270
1.25	28 / 350	44 / 550
1.5	41 / 615	63 / 945
1.75	55 / 962	86 / 1,505
2	73 / 1,460	113 / 2,260
2.25	94 / 2,115	146 / 3,285
2.5	116 / 2,900	180 / 4,500
2.75	143 / 3,932	222 / 6,105
3	173 / 5,190	269 / 8,070
3.25	206 / 6,695	320 / 10,400
3.5	242 / 8,470	375 / 13,125
3.75	280 / 10,500	435 / 16,312

4	321 / 12,840	499 / 19,960

13. Install second top nut on each bolt to the snug tight condition.

14. After all prior steps are completed and all elements of the structure are fully erected, the Contractor shall perform an ultrasonic test on all anchor bolts in accordance with ASTM E114 - Ultrasonic Pulse Echo Straight Beam Testing by the Contact Method. Ultrasonic testing personnel shall be qualified in accordance with ASNT SNT-TC-1A Level II and certified by the VDOT Materials Division. Equipment shall be qualified in accordance with AWS D1.5 Section 6, Part C. Anchor bolts shall have no indications that are above 10% Full Screen Height at the prescribed scanning level. All indications shall be noted on the test report and submitted to the Engineer and the VDOT Materials Division. A copy of the report, for both structures with and without indications, shall be submitted to the District Bridge Office and the Engineer.

Single-nut connections

Single-nut connections installation procedures shall conform to the following:

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. If anchor bolt(s) are not plumb (vertical), determine if beveled washer(s) may be required prior to erection of the structure. Beveled washers shall be used under the nut if any face of the base plate/T-base has a slope greater than 1:20 and/or if any nut could not be brought in firm contact with the base plate/T-base.
3. Clean and lubricate the exposed thread of all anchor bolts, nuts, and bearing surfaces of the nuts and washers. Ensure that the threads of the rod, nuts, and bearing surfaces of nuts and washers are free of dirt, concrete, debris, or other contaminants since these can lead to improper tightening. 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. Verify that the nuts can be turned onto the bolts the full length of the threads by hand.
5. The post, end frame or T-base 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.
6. Tighten the top nuts incrementally to the manufacturer recommended torque value using a calibrated torque wrench in star pattern. The torque should be applied in a star 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.
7. 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.

8. For T-base tightening: after the installation of the T-base, a manufacturer recommended tightening 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.