THE RELATIONSHIP BETWEEN TORQUE, TENSION, AND NUT ROTATION OF LARGE DIAMETER ANCHOR BOLTS
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Research and Technology Section
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Michigan Transportation Commission
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Action Plan

Results from this investigation have been used to specify the anchor bolt nut tightening procedures in the Special Provision for Sign Support and Light Standard Anchor Bolts, and for the Maintenance Division's tightening procedures. Action items relative to anchor bolt tightening are as follows:

1.) Specify the addition of beeswax to the bearing face of the top nut and to the internal threads prior to placing the nut on the anchor bolt.

2.) Specify 1/3 turn additional tightening past the snug condition for 1" to 2 1/4" - 8 UN anchor bolts and 1" to 1 1/4" - UNC anchor bolts. Specify 1/6 turn additional tightening past the snug condition for 1 1/4" to 2 1/4" - UNC anchor bolts.

3.) Determine a torque value that is applied to the anchor bolt a minimum of 48 hours after final tightening using $K = 0.12$ in the equilibrium equation $T = KPD$.

4.) Establish the maximum torque values that can be applied during maintenance anchor-bolt tightening as the maximum torque applied during this investigation.

5.) Monitor field installations for effects of cold weather and variation in the snug-tight condition. This monitoring will be done by the Materials and Technology Division.

6.) Distribute this report to Design, Construction, and Maintenance Divisions, along with the District offices.
Introduction

The purpose of this investigation was to determine the relationship between torque, tension, and nut rotation of the large-diameter anchor bolts used on cantilever sign supports. This research was in response to concerns about loose nuts found on these anchor bolts during field inspections of in-service sign supports, along with concerns regarding an unspecified tightening procedure. Results of this investigation were used to determine the appropriate anchor-bolt tightening procedure and to determine whether or not turning the nut past the snug position imparts the desired amount of tension in the anchor bolt. This investigation also determined the appropriate torque for checking anchor-bolt installations in the field, the effects of bolt relaxation, and any problems of thread stripping from tightening.

The proper tightening of anchor bolts is imperative to eliminate both nut loosening and fatigue overloading. Prior to 1991, anchor-bolt installations required the Unified National Coarse (UNC) thread series, which has a thread pitch that increases with the diameter. Current anchor-bolt installations require the 8 Unified National (SUN) thread series, a series with a uniform pitch for various diameter bolts, typically used as a substitute for the UNC series for diameters larger than one inch. Since the Maintenance Division tightened anchor bolts on existing cantilever sign supports, which have a different thread series than the current ones, testing was done on the coarse-pitch-thread anchor-bolt types as well as the new type that uses an SUN thread series. This research will be useful to the Construction and Maintenance Divisions when tightening new and in-service anchor bolts on cantilever sign supports, high-mast luminaires, light standards, and sign supports in general.

Test Methods

The testing procedure consisted of placing a large-diameter anchor bolt in a simulated steel base plate of the proper thickness, with a washer and nut on each side (see Figure 1 for assembled test specimen). All materials were galvanized except the base plate. Anchor bolts, nuts, and washers used for the SUN thread series bolt tests came from acceptance samples submitted for testing from Michigan Department of Transportation (MDOT) projects. Maintenance warehouse bolts, nuts, and washers were used for the UNC series bolt testing. Mechanical properties of these bolts are shown in Table 1. Nuts for the anchor bolts were stamped with DH or 2H markings, indicating that they met ASTM A-563 or A-194 grade, respectively. Base-plate thickness for the diameter and thread pitch of the bolt tested corresponded to the design standard for the cantilever sign base using that specific anchor bolt. Testing was done in the Structural Research Laboratory at a temperature of about 70°F.
Initially, two strain gages were attached to an anchor bolt that had its threads milled off at diametrically opposite locations. The anchor bolt with the strain gages attached was calibrated by using known loads and determining the corresponding strains. Keeper bars were added to the base plates to prevent the bottom nut from rotating. Two 23/4"-4UNC (Table 6, Sample Identifications A1 and B1) anchor bolts were tested using this configuration. However, the method of testing was subsequently changed because of the lengthy preparation time required for each anchor bolt. The steel base plate was then instrumented with strain gages to determine the bolt load after applying a given torque or nut rotation. Four strain gages were mounted 90° apart on the inside of the bolt hole in the base plate. These base plates were calibrated by compressing the plate incrementally with a known load, using washers and nuts as a footprint, and recording the corresponding strain. Keeper bars were added to the base plate to prevent rotation of the bottom nut. The remaining anchor bolts were tested using this method. During all testing, strain was recorded when the nut was rotated to a specified torque or degrees turned, and later converted to a bolt load.

A template with two-degree graduations was attached to each nut to measure the degrees the nut was rotated. Snug tightening of the anchor bolts was done using a 34-inch long adjustable wrench. Final tightening of the anchor bolts past snug was accomplished with a hydraulic wrench with maximum torque capacity of 11,400 ft-lbs.

All anchor bolts were ultrasonically tested for defects before and after tightening. The testing procedure consisted of the following steps:

1.) Visually inspect the anchor bolt and ultrasonically test the anchor bolt for flaws.

2.) Apply beeswax to the bearing face of the top nut and internal diameter of the top nut.

3.) Assemble the anchor bolt, nuts, and washers in steel base plate.

4.) Snug tighten the top nut of the anchor-bolt using the full effort of one person.

5.) Record strain in the fixture.

6.) Incrementally tighten the top nut of the anchor bolt.

7.) Record strain in fixture, torque applied, and degrees of nut rotation.

8.) Release the load.
9) Visually inspect the anchor bolt and ultrasonically test the anchor bolt for flaws.

Loading the bolt to a snug tight condition was performed by various sized individuals, providing different snug tension in the anchor bolts.

Relaxation of bolt tension was checked by tightening the bolt to a predetermined load, then remeasuring the load at a later time. A third galvanized washer was added to the assembly to account for zinc flow under load, because the base plate was a non-galvanized metal. The extra washer was added only for the long-term relaxation test.

Temperature effects on the anchor-bolt tightening procedure were not investigated. The beeswax added prior to assembly could stiffen and prevent proper tightening. Temperature effects could be field monitored for any adverse effect low temperatures might have on the tightening.

Test Results

Tables 2 through 6 list the data obtained from the laboratory testing: the sample identification, bolt load, corresponding torque, and degrees turned are shown. Graphic representations of load versus degrees turned and load versus torque are shown in Figures 2 to 6, with corresponding data shown in Tables 2 to 6. A listing of pertinent data from these tables is summarized in Table 7.

In an effort to predict the relationship between torque and tension on the anchor bolt, the equilibrium equation \( T = KDF \) was used, where \( T = \) torque, \( D = \) nominal diameter of bolt, \( F = \) induced force (clamp load), and \( K = \) empirical constant accounting for friction and variable diameter of the bolt at the threads. Using this equation, the constant \( K \) is estimated to be 0.12 when beeswax is added to the nut-bearing boss and internal thread. A review of Figures 2 through 6 indicates that \( K \) equal to 0.12 is a reasonable value when considering the data scatter and conservative approach required for preventing thread stripping from over torquing. The value of \( K = 0.12 \) is shown in the referenced figures.

Figures 2b through 6b show a load at zero torque, which is not representative because a torque was applied to the bolt when it was initially snug tightened. As previously noted, the snug-tight condition was obtained with a 34-inch long wrench. Unfortunately, because this wrench was not a torque wrench, only load could be recorded for the initial snug condition. The wrench used was purposely chosen to simulate actual equipment that was being used by MDOT's Maintenance Division for tightening anchor bolts. The snug tight load is shown in Figure 2b through 6b at zero torque because there was an unknown torque applied to the bolt at the snug-tight condition. However, the graph lines in the figures start at the origin and extend to the
second set of data where torque was recorded in order to reflect the actual behavior of the anchor bolts.

The amount the top nuts were rotated was recorded in degrees after the snug-tight condition was achieved. Once snug tightened, a mark was made on the nut corresponding to the zero point on the template and would indicate number of degrees turned during the subsequent tightening. Therefore, Figures 2a through 6a show a load at zero degrees turned because a load was present after snug tightening, but the degrees turned were not recorded until after the snug condition was established.

Ultrasonic test results indicated no flaws in any of the bolts after testing. However, an apparent crack was visible in the root thread of one 2\frac{1}{4}'' - 4 UNC bolt that received a high torque and high load during testing (Table 6, Sample Identification 1001, turned to 200 degrees, 7,875 ft-lbs of torque, and 350 kips of load). The galvanized coating was chemically removed from the crack area to reveal the base metal. Microscopic inspection detected no crack, only a slight galling of base metal was present. It is important to note that turning the nut significantly past snug-tight condition demonstrated that the bolt can withstand a considerable amount of load above the yield point, without a major negative effect on the bolt.

Bolt-relaxation data from zinc flow are listed in Table 6 under B1, Relaxation Test. In this case, a third washer was added to replace the zinc absent on the instrumented base plate. These data show that most relaxation occurred within the first 24 hours. Relaxation tests were also performed on different bolts (see Tables 2, 4, 5, and 6); however, in these cases a third washer was not added, and the bolt was only examined once for load loss. Sample B1 was the only bolt for which relaxation data were monitored over different time increments to determine load loss. Relaxation of bolt load is in the range of two to six percent, as shown in Table 7.

Recommendations

Results from this investigation will be used for the anchor-bolt nut-tightening procedures specified in the Special Provision for Sign Support and Light Standard Anchor Bolts, and for the Maintenance Division's tightening procedures. Recommendations relative to anchor-bolt tightening are as follows:

1.) Specify the addition of beeswax to the bearing face of the top nut and to the internal threads prior to placing the nut on the anchor bolt. This is done in order to provide less variable thread friction and torque requirements for tightening.

2.) Specify 1/3 turn additional tightening past the snug condition for 1" to 2\frac{1}{4}'' - 8 UN anchor bolts and 1" to 1\frac{1}{4}'' - UNC anchor bolts. Specify 1/6 turn

-5-
additional tightening past the snug condition for 1 1/4" to 2 1/2" - UNC anchor bolts. This pretensioning is intended to prevent nuts from loosening and increase the fatigue life of the anchor bolt.

3.) Use \( K = 0.12 \) in the equilibrium equation \( T = KPD \) to determine a torque value that is applied to the anchor bolt a minimum of 48 hours after final tightening in order to check the nut tightness. This value of \( K = 0.12 \) accounts for the effects of relaxation of bolt load due to zinc flow, and is intended to be a value that prevents bolt damage from occurring during the nut tightness check.

4.) Establish the maximum torque values that can be applied during maintenance anchor-bolt tightening as the maximum torque applied during this investigation. This maximum torque value varies based on the diameter of the anchor bolt and is shown in Table 7.

5.) Monitor field installations for the effects of cold weather and any variation in the snug-tight condition. This monitoring will be done by the Materials and Technology Division. Changes to the tightening procedure may be required based on data from the field experience.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Load (vps)</th>
<th>Torque (lb-in)</th>
<th>Degrees Turned</th>
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<tbody>
<tr>
<td>100</td>
<td>57.0</td>
<td>1132</td>
<td>90</td>
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<td>150</td>
<td>60.0</td>
<td>1092</td>
<td>120</td>
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<td>200</td>
<td>64.0</td>
<td>1200</td>
<td>150</td>
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<tr>
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<tr>
<td>300</td>
<td>80.0</td>
<td>1132</td>
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<th>Torque (lb-in)</th>
<th>Degrees Turned</th>
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<tr>
<td>300</td>
<td>80.0</td>
<td>1132</td>
<td>360</td>
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*3% (25.2 kpsi) load loss after 16.5 hours of relaxation

Table 2 - 1/2" Diameter, 8UN Threads
### Table 3 - 1 1/2" Diameter, 6UNC Threads

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<tr>
<th>SAMPLE</th>
<th>LOAD (lbs)</th>
<th>TORQUE (lbf-in)</th>
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<td>B</td>
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<td>116.0</td>
<td>2485</td>
<td>53.7</td>
</tr>
<tr>
<td>E</td>
<td>116.0</td>
<td>2485</td>
<td>53.7</td>
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<tr>
<td>F</td>
<td>67.0</td>
<td>1879</td>
<td>50.6</td>
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<td>G</td>
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### Table 4 - 2" Diameter, 4 UNC Threads

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Table 5 - 2 1/2" Diameter, SUN Threads

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Table 6 - 2 1/2" Diameter, KUNC Threads

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<tr>
<th>SAMPLE</th>
<th>LOAD</th>
<th>PERCENT LOAD</th>
<th>TIME OF RELAXATION</th>
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<td>122</td>
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<td>0.12%</td>
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<td>0.12%</td>
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<td>3.3%</td>
<td>0.12%</td>
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<tr>
<td>101</td>
<td>4890</td>
<td>3.3%</td>
<td>0.12%</td>
</tr>
<tr>
<td>100</td>
<td>6300</td>
<td>3.3%</td>
<td>0.12%</td>
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<td>7800</td>
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<tr>
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<td>9500</td>
<td>3.3%</td>
<td>0.12%</td>
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<td>950</td>
<td>11675</td>
<td>3.3%</td>
<td>0.12%</td>
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* AN 180 kp LOAD LOSS AFTER 64 HOURS OF RELAXATION
### Table 7 — Summary of Data

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<thead>
<tr>
<th>Bolt/Thread Series</th>
<th>1-1/2, UNC</th>
<th>1-1/2, 4UNC</th>
<th>2-3/4, 1-1/2 UNC</th>
<th>2-3/4, UNC</th>
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<tbody>
<tr>
<td>Tensile Range (ksi)</td>
<td>21.0 - 24.0</td>
<td>17.0 - 20.4</td>
<td>13.4 - 15.5</td>
<td>16.7 - 20.1</td>
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<td>Load, Minimum (ksi)</td>
<td>75.0</td>
<td>70.0</td>
<td>120.0</td>
<td>120.0</td>
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<td><strong>P</strong>, Minimum (ksi)</td>
<td>75.0</td>
<td>94.2</td>
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<td>% of Tensile Load when Stranged</td>
<td>27% - 42%</td>
<td>24% - 46%</td>
<td>10% - 17%</td>
<td>8% - 13%</td>
</tr>
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<td>Minimum Torque (5'-10')</td>
<td>3970</td>
<td>2022</td>
<td>4000</td>
<td>5133</td>
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<tr>
<td>Minimum Load (ksi)</td>
<td>95.2</td>
<td>150.6</td>
<td>221.8</td>
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<td>Minimum Degree Turned</td>
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<td>541</td>
<td>290</td>
<td>360</td>
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<td><strong>5%</strong> - Load Range at 1/3 Turn (ksi)</td>
<td>76 - 81</td>
<td>56 - 67</td>
<td>112 - 160</td>
<td>222 - 373</td>
</tr>
<tr>
<td><strong>3%</strong> - Load Range at 1/6 Turn (ksi)</td>
<td>76 - 81</td>
<td>56 - 67</td>
<td>112 - 160</td>
<td>222 - 373</td>
</tr>
</tbody>
</table>

* Tensile load is based on applying the minimum yield stress (FY) of 30 ksi for the bolt in the weakest area (A_f).

** P** is based on P_f. P minimum from tensile test, see Table 1.

*** Data was interpolated from Figures 2b - 6a.

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**Figure 1 — Typical Assembled Test Specimen**
Figure 2a - 1 1/2" Dia., 8UN

Figure 2b - 1 1/2" Dia., 8UN
Figure 3a - 1 1/2" Dia., 6UNC

Figure 3b - 1 1/2" Dia., 6UNC
Figure 4a - 2" Dia., 4 1/2 UNC

Figure 4b - 2" Dia., 4 1/2 UNC
Figure 5a - 2 1/2" Dia., 8UN

Figure 5b - 2 1/2" Dia., 8UN
Figure 6a - 2 1/2" Dia., 4UNC

Figure 6b - 2 1/2" Dia., 4UNC