MICHIGAN DEPARTMENT OF TRANSPORTATION
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THE RELATIONSHIP BETWEEN TORQUE, TENSION, AND NUT ROTATION OF LARGE DIAMETER ANCHOR BOLTS

MICHIGAN DEPARTMENT OF TRANSPORTATION

MATERIALS and TECHNOLOGY DIVISION

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THE RELATIONSHIP BETWEEN TORQUE, TENSION, AND NUT ROTATION OF LARGE DIAMETER ANCHOR BOLTS

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Research and Technology Section
Materials and Technology Division
Research Project 91 TI-1556
Research Report No. R-1330

Lansing, October 1994

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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 2½" - 8 UN anchor bolts and 1" to 1½" - UNC anchor bolts. Specify 1/6 turn additional tightening past the snug condition for 1¾" to 2½" - 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 (8UN) 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 8UN 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 8UN 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 A194 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 2½"-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 face 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 2½" - 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 2½" - 8 UN anchor bolts and 1" to 1¾" - UNC anchor bolts. Specify 1/6 turn additional tightening past the snug condition for 1½" to 2½" - 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.

Bolt Diameter and Thread Series	1-1/2", 8UN	1-1/2", 6UNC	2", 4-1/2 UNC	2-1/2", 8UN	2-1/2", 4UNC
Quantity Tested	6	1	1	6	4
Yield Strength Average (psi)	62,100	67,000	103,000	56,900	67,250
Yield Strength Range (psi)	51,000 – 68,500			54,000 – 58,500	66,500 – 67,000
Tensile Strength Average (psi)	96,750	107,000	124,000	95,100	103,750
Tensile Strength Range (psi)	95,000 – 97,500			93,000 – 97,500	102,000 – 106,000
Elongation Average (%)	30	25	14	21	25
Reduction of Area Average (%)	46			32	

Table 1 – Mechanical Properties

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
157	30.2	snug	0
	70.3	1125	89
	78.4	1350	133
	90.8	1800	225
	94.1	2250	275
	95.5	2700	284
159	22.6	snug	0
	69.7	1125	98
	75.9	1350	111
	85.7	1575	165
235	31.0	snug	0
	67.5	1125	25
	84.3	1350	34
	85.2	1575	41
	85.7	1800	64
	84.3	2025	73
	88.8	2475	119
	89.1	2925	129
236	22.6	snug	0
	56.3	1125	38
	67.5	1350	49
	75.9	1800	67
	76.5	2250	114
	77.6	2475	121
	* 75.3		121

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
648	19.8	snug	0
	61.9	1125	37
	73.9	1350	47
	80.3	1575	54
	78.1	1800	62
	78.7	2250	100
	77.3	2475	109
	77.5	2700	117
	81.5	2925	135
649	22.6	snug	0
	66.1	1125	36
	73.1	1350	41
	81.0	1575	50
	75.9	1800	57
	76.7	2250	94
	78.7	2700	120
	75.9	3375	159

* 3 % (2.3 kips) LOAD LOSS AFTER 16.5 HOURS OF RELAXATION

Table 2 – 1 1/2" Diameter, 8UN Threads

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
F	19.0	snug	0
	60.2	1125	68
	67.5	1350	72
	71.7	1575	101
	74.5	1800	118
G	32.4	snug	0
	76.0	1125	47
	79.3	1350	78
	81.5	1575	116
	84.3	1800	156
K	17.0	snug	0
	64.7	1125	59
	73.1	1350	70
	78.1	1575	115
	78.1	1800	124

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
M	22.6	snug	0
	59.1	1125	26
	66.1	1350	52
	67.5	1575	94
	71.7	1800	117
NM	25.4	snug	0
	67.5	1125	22
	84.3	1350	51
	95.5	1575	82
	118.0	1800	146
P	18.4	snug	0
	61.9	1125	44
	72.5	1350	60
	73.1	1575	91
	71.7	1800	97
	78.7	2250	139
	78.7	2925	241

Table 3 – 1 1/2" Diameter, 6UNC Threads

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
A	20.0	snug	0
	58.3	1125	17
	87.0	1575	28
	119.0	2025	39
	144.1	2475	49
	167.3	2925	59
	177.8	3375	64
	194.7	3825	71
	212.9	4500	88
B	18.1	snug	0
	62.7	1125	27
	95.3	1575	40
	124.3	2025	54
	161.0	2475	88
	161.0	2588	90
C	20.0	snug	0
	38.8	1125	13
	55.9	1575	23
	73.9	2025	33
	88.5	2475	43
	98.2	2925	49
	106.0	3375	56
	112.7	3825	62
	115.6	3938	66

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
D	15.1	snug	0
	53.4	1125	17
	83.6	1575	28
	121.0	2025	40
	153.8	2475	56
	178.8	2925	75
	180.0	3038	79
E	12.6	snug	0
	35.3	1125	16
	54.4	1575	25
	78.8	2025	36
	101.1	2475	48
	117.6	2925	58
	131.1	3375	70
	148.0	3825	96
	189.9	4500	239
I	21.5	snug	0
	59.3	1125	15
	98.2	1575	29
	140.2	2025	45
	170.6	2250	71
	*161.0		71

Table 4 – 2" Diameter, 4 1/2 UNC Threads

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
651	29.2	snug	0
	91.7	2250	40
	104.2	2700	50
	129.2	3375	60
	158.3	4050	71
	179.2	4500	76
	201.7	4950	84
	215.0	5175	90
	225.0	5400	92
	231.7	5625	96
	240.0	5850	100
	245.0	6075	106
	250.0	6300	115
	242.0	6300	118
652	16.8	snug	0
	33.3	1125	12
	41.7	1350	16
	64.2	1800	28
	85.0	2250	34
	108.3	2700	42
	140.0	3375	53
	177.5	4050	68
	195.8	4500	82
	204.2	4950	92
	233.3	5175	132
	241.7	5175	140
653	29.2	snug	0
	94.2	2250	32
	116.7	2700	40
	141.7	3375	50
	166.7	4050	60
	181.7	4500	68
	185.8	5175	76
	200.0	5062	120
	200.0	5850	144
	200.0	6300	146
	214.2	6750	182
	214.2	7425	186

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
654	20.8	snug	0
	83.3	2250	42
	110.0	2700	52
	150.0	3375	65
	191.7	4050	80
	204.2	4500	90
	206.7	4725	96
	200.0	4950	103
	200.0	5175	110
	200.0	5400	117
	195.8	5625	120
	* 191.7		120
	200.0	5625	123
	245.8	6300	221
	258.3	7200	247
	266.7	7875	264
	241.7	7875	300
706	16.7	snug	0
	83.3	2250	37
	112.5	3375	60
	129.2	4050	74
	145.8	4500	81
	183.3	4950	92
	211.1	5175	110
	213.3	5400	112
	222.2	5625	120
707	25.0	snug	0
	83.3	2250	32
	125.0	3375	54
	151.7	4050	69
	216.7	4950	145

* 2 % (4.1 kips) LOAD LOSS AFTER 17 HOURS OF RELAXATION

Table 5 – 2 1/2" Diameter, 8UN Threads

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
1001	12.5	snug	0
	94.2	2250	27
	125.0	2700	35
	162.5	3375	43
	195.8	3825	49
	210.8	4050	52
	220.8	4275	54
	233.3	4500	56
	241.7	4837	60
	350.0	7875	200
1002	25.0	snug	0
	95.8	2250	20
	120.0	2700	25
	150.0	3375	32
	191.7	4050	42
	210.8	4500	46
	225.0	4950	51
	229.2	5287	62
	*219.2		62
1003	17.5	snug	0
	81.7	2250	20
	100.0	2700	24
	133.3	3375	30
	156.7	3825	34
	191.7	4500	40
	208.3	4950	44
	225.0	5400	49
	270.8	5850	60
1004	16.7	snug	0
	100.0	2250	20
	144.7	2700	26
	200.0	3375	36
	220.8	3600	40
	245.8	4050	48
	279.2	4500	60

* 4% (10 kips) LOAD LOSS AFTER 64 HOURS OF RELAXATION

SAMPLE I.D.	LOAD KIPS	TORQUE FT-LBS	DEGREES TURNED
A1	21	snug	0
	72.2		10
	106.4		20
	119.1	2475	24
	133.8		30
	149.2	2925	32
	167.0		39
	179.7	3375	41
	209.7		50
	238.4		58
	266.8	4050	61
**B1	24.9	snug	0
	49.5		10
	83.2		20
	97.7	2475	23
	115.6	2925	30
	132.1	3375	33
	145.4	3600	39
	149.3		40
	160.0	3825	43
	170.0	4050	46
	173.0	4275	49
	174.6	4500	50
	183.7	4950	51
	235.7	5400	60

** B1 RELAXATION TEST

LOAD KIPS	PERCENT LOAD LOSS	TIME OF RELAXATION
237.4		INITIAL LOAD
229.9	3.2%	24 HRS./1 DAY
229.4	3.4%	48 HRS./2 DAYS
227.7	4.1%	168 HRS./7 DAYS
227.1	4.3%	288 HRS./12 DAYS

Table 6 – 2 1/2" Diameter, 4UNC Threads

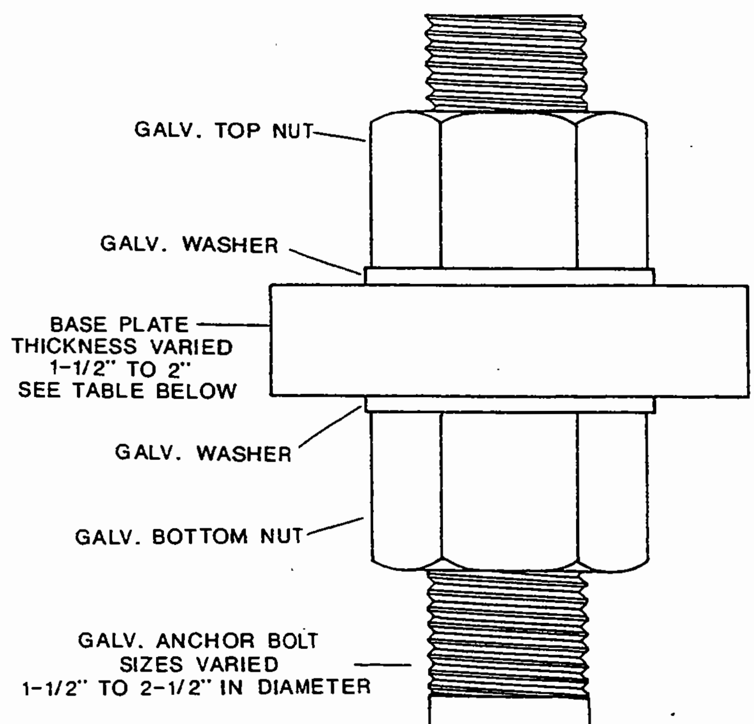
Bolt Diameter and Thread Series	1-1/2", 8UN	1-1/2", 6UNC	2", 4-1/2UNC	2-1/2", 8UN	2-1/2", 4UNC
Snug Range (kips)	19.8 - 31.0	17.0 - 32.4	12.6 - 21.5	16.7 - 29.2	12.5 - 25.0
* Desired Load (kips)	74.5	70.5	125.0	222.0	200.0
** P_y Minimum (kips)	76.0	94.5	257.5	239.8	266.0
% of Desired Load when Snugged	27% - 42%	24% - 46%	10% - 17%	8% - 13%	6% - 13%
Maximum Torque (ft-lb)	3375	2925	4500	7875	7875
Maximum Load (kips)	95.5	118.0	212.9	266.7	350.0
Maximum Degrees Turned	284	241	239	300	200
*** 8UN - Load Range at 1/3 Turn (kips)	76 - 89			196 - 242	
*** UNC - Load Range at 1/6 Turn (kips)		56 - 87	112 - 168		228 - 279
Relaxation	3% loss of load after 16.5 hours		6% loss of load after 68 hours	2% loss of load after 17 hours	4% loss of load after 64 hours, more on Table 6

* Desired load is based on applying the minimum yield stress (F_y) of 50 ksi for the bolt to the tensile stress area (A_t).

** P_y based on $F_y A_t$. F_y minimum from testing used, see Table 1.

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

Table 7 - Summary of Data



Bolt Size	Base Plate Thickness
1-1/2", 8UN	1-1/2"
1-1/2", 6UNC	1-1/2"
2", 6UNC	1-5/8"
2-1/2", 4UNC	1-3/4"
2-1/2", 8UN	2"

Figure 1 - Typical Assembled Test Specimen

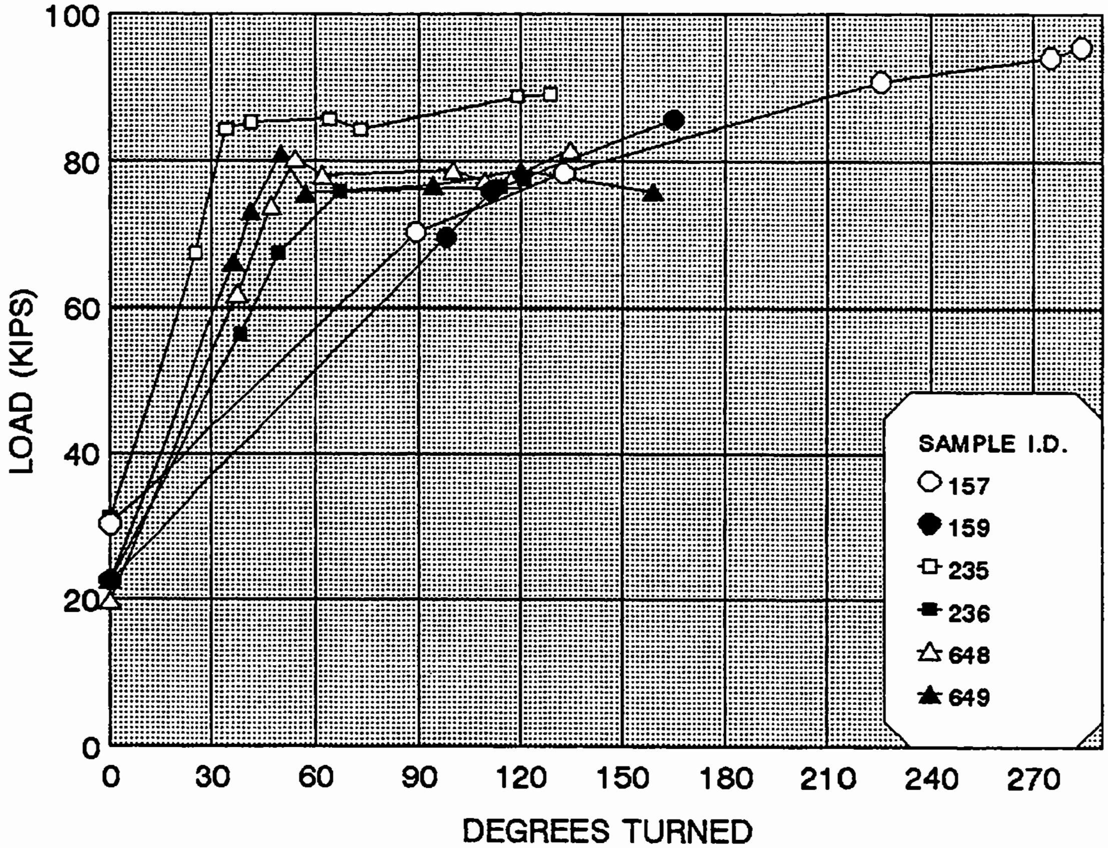


Figure 2a - 1 1/2" Dia., 8UN

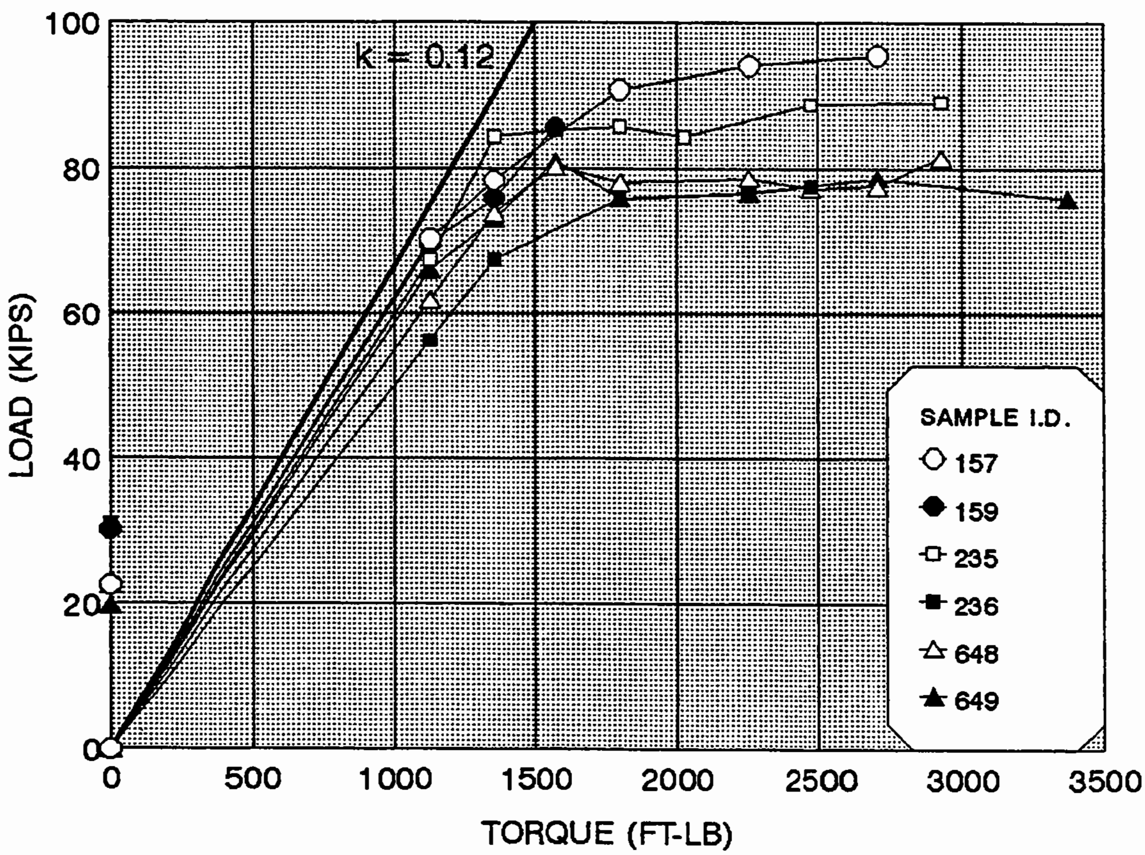


Figure 2b - 1 1/2" Dia., 8UN

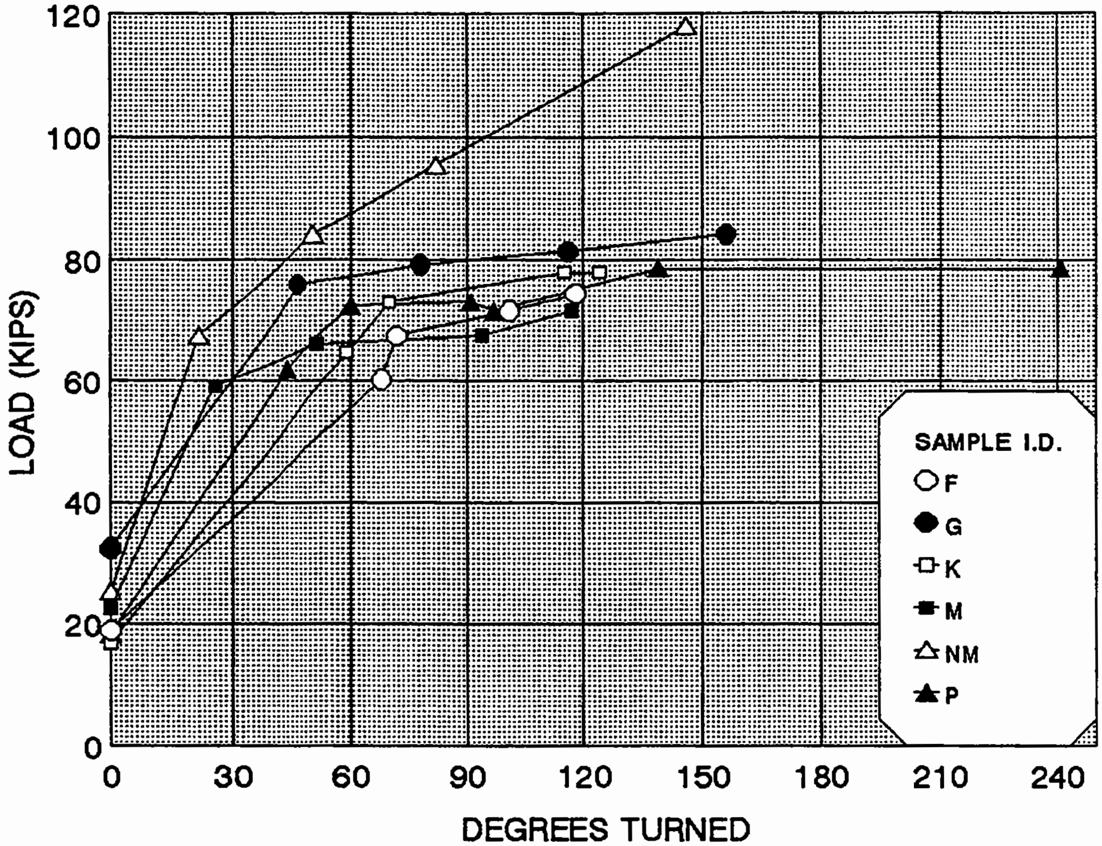


Figure 3a - 1 1/2" Dia., 6UNC

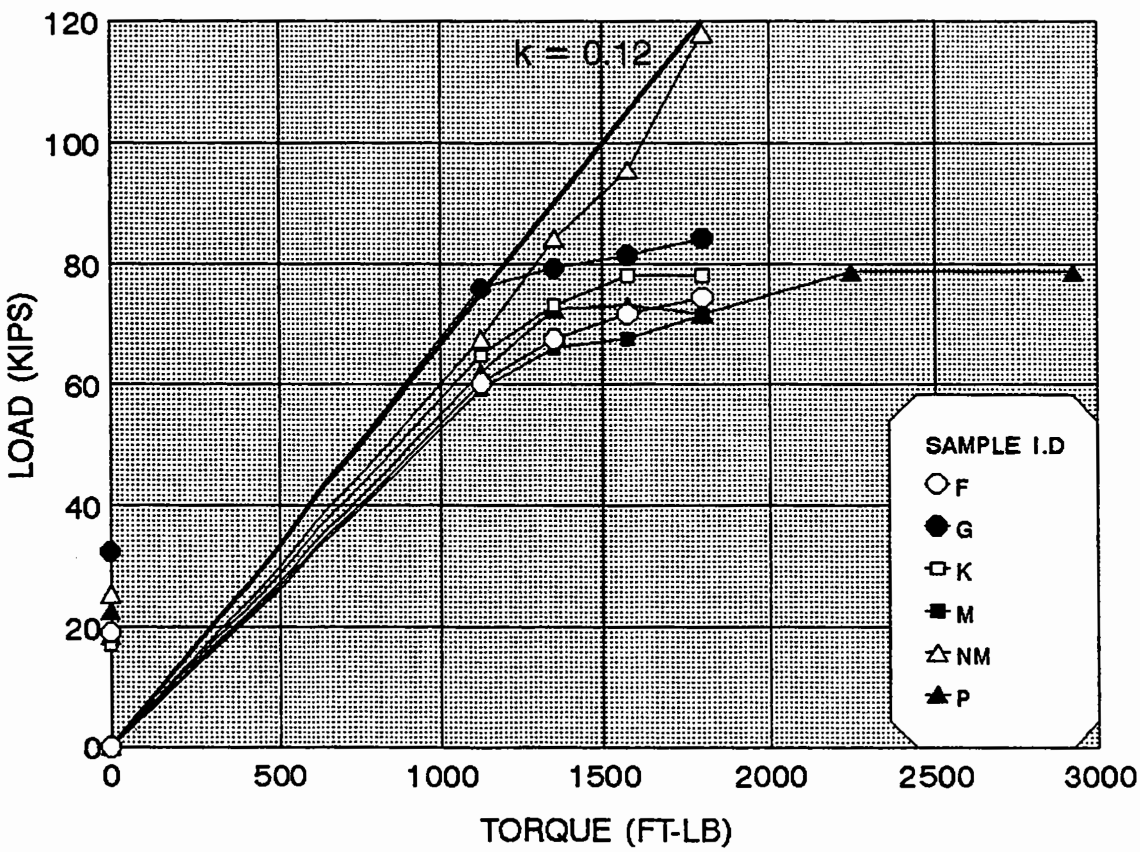


Figure 3b - 1 1/2" Dia., 6UNC

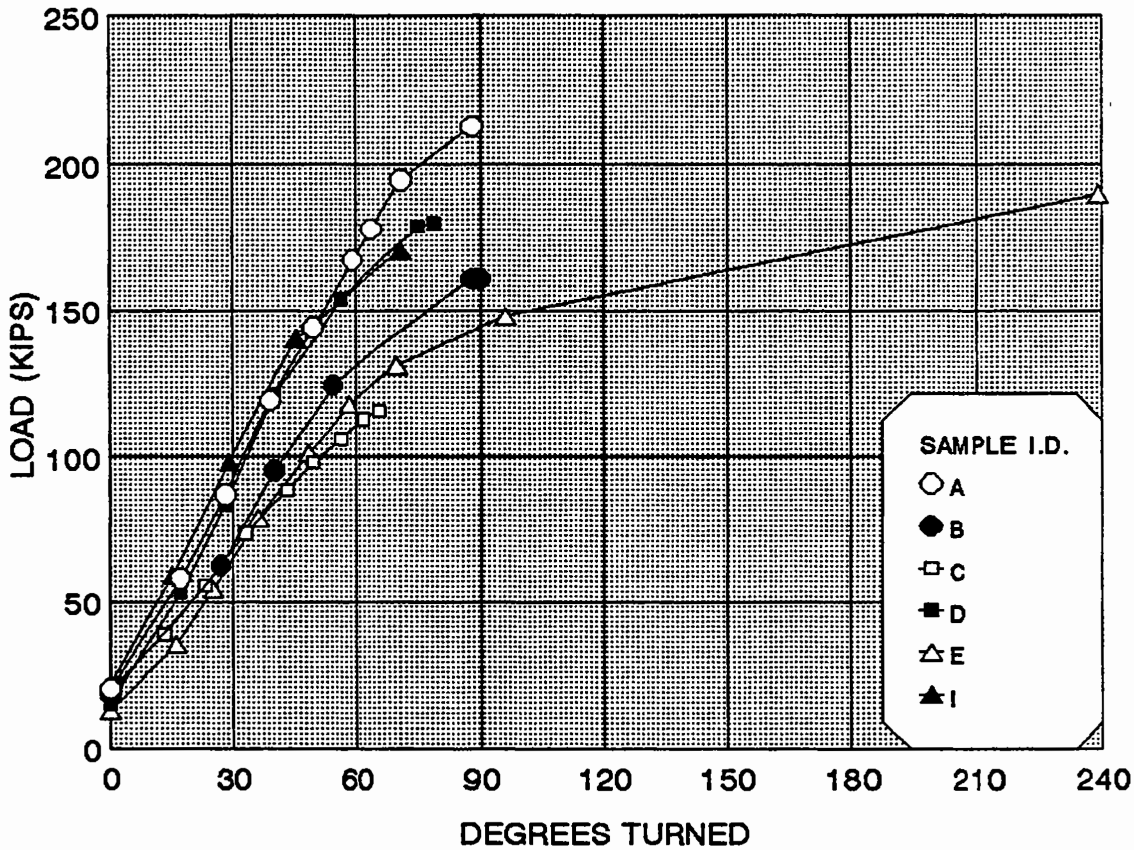


Figure 4a - 2" Dia., 4 1/2 UNC

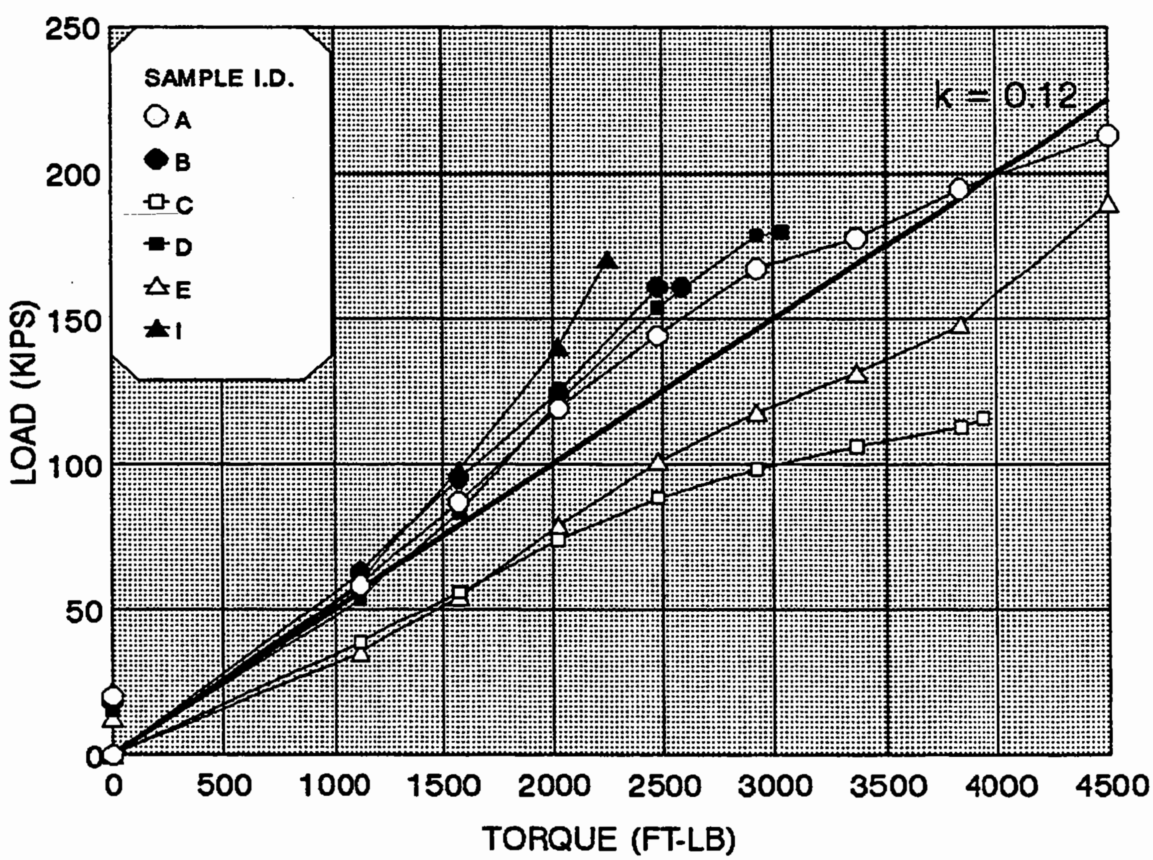


Figure 4b - 2" Dia., 4 1/2 UNC

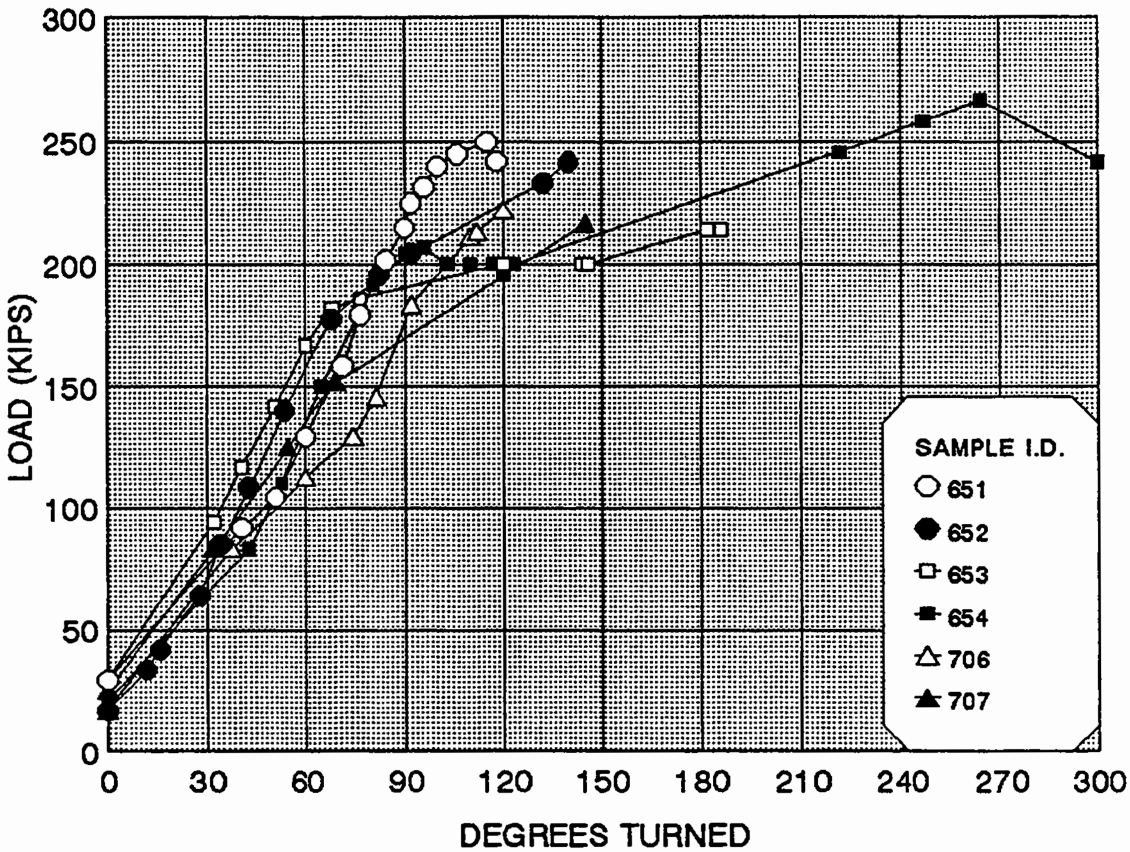


Figure 5a - 2 1/2" Dia., 8UN

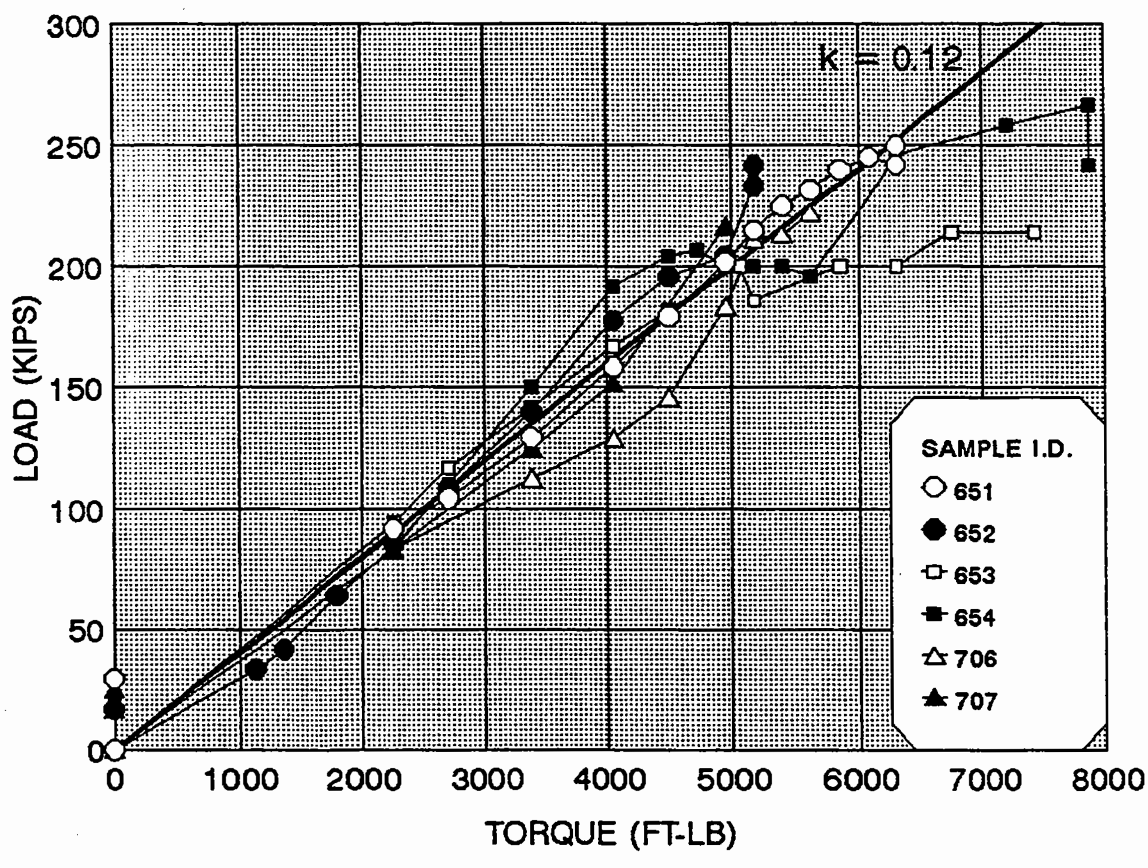


Figure 5b - 2 1/2" Dia., 8UN

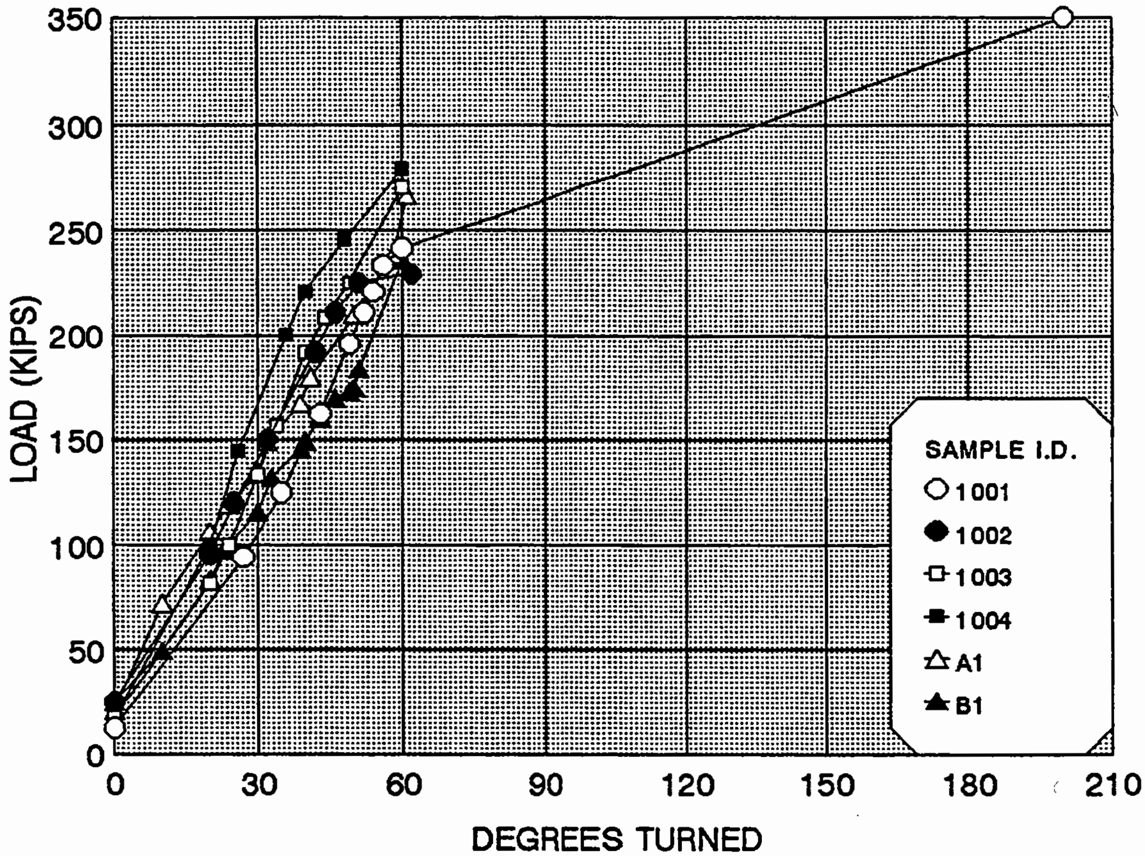


Figure 6a - 2 1/2" Dia., 4UNC

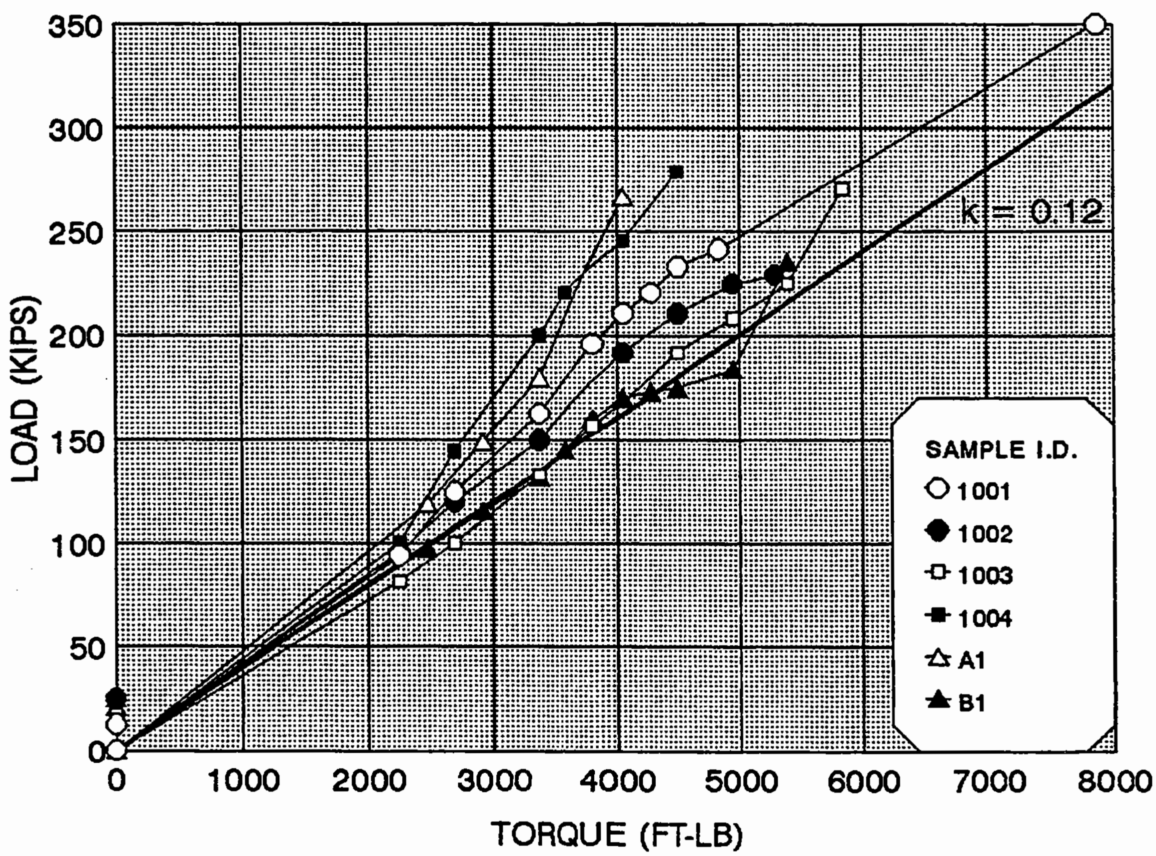


Figure 6b - 2 1/2" Dia., 4UNC