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John P. Dusel, Robert Travis and J. Robert Stoker

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It was found that of the variables evaluated preload was the most important factor affecting fatigue life. Anchor bars with single nuts and preloaded their full length to near yield had the longest fatigue lives, with an endurance limit near the yield stress of the bar. The poorest fatigue performance was exhibited by the unpreloaded double nut anchor bar system currently used by Caltrans. A considerable increase in fatigue life of between two and ten times was obtained for this double nut system by tightening top nuts 1/3 turn past snug tight. Highly preloaded cap screws exhibited long fatigue lives and were affected little by prying loads in specimens tested.

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STATE OF CALIFORNIA
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DIVISION OF ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

DETERMINATION OF FATIGUE CHARACTERISTICS OF HOT-DIP GALVANIZED A307 AND A449 ANCHOR BARS AND A325 CAP SCREWS

Study Supervised by .... Mike Nagai, P.E.
Eric F. Nordlin, P.E.

Principal Investigator .... J. Robert Stoker, P.E.

Co-Principal Investigator .... John P. Dusel, Jr., P.E.

RAYMOND A. FORSYTH, P.E.
Chief, Office of Transportation Laboratory

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CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quantity	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mmm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2)	6.432×10^{-4}	square metres (m^2)
	square feet (ft^2) acres	.09290 .4047	square metres (m^2) hectares (ha)
Volume	gallons (gal)	3.785	litres (l)
	cubic feet (ft^3)	.02832	cubic metres (m^3)
	cubic yards (yd^3)	.7646	cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G)	9.807	metres per second squared (m/s^2)
Weight Density	pounds per cubic (lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) kips (1000 lbs)	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British thermal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (ft-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch (ksi $\sqrt{in}$)	1.0988	mega pascals $\sqrt{metre}$ (MPa $\sqrt{m}$)
	pounds per square inch square root inch (psi $\sqrt{in}$)	1.0988	kilo pascals $\sqrt{metre}$ (KPa $\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{tF - 32}{1.8} = tC$	degrees celsius (°C)

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

1. INTRODUCTION

1.1 Background

The service life of threaded fasteners subjected to fatigue loading such as those used in structural supports for highway signs, luminaires, and traffic signals has long been a difficult thing for design engineers to accurately predict. While theoretical solutions have been developed for determining the endurance limits of individual fasteners under idealized simplified loading situations, the complexity of actual structural connections and variations in joint geometry make predicting fatigue life accurately and designing connectors with a sense of both economy and adequate safety an extremely difficult task. Other variable factors which complicate proper design even further include the effects of grip length, fastener diameter, type of steel, internal stress range, preload, joint stiffness, external load applied to the joint, combined loading and prying action, amount of preload loss due to compression of galvanizing, and the number and magnitude of cyclic stresses applied to a fastener in its expected life. Because of the uncertainty of many of these factors, the allowable design stresses currently used for determining sizes of fasteners used in highway sign, luminaire, and traffic signal supports have appeared to many to be overly conservative.

1.2 Purpose of Research

The purpose of this research is to evaluate the fatigue limits of various hot-dip galvanized anchor bars and cap screws typically used by the California Department of Transportation (Caltrans) in structural supports for highway signs, traffic signals and luminaires, and to establish S-N curves for designers to use.

1.3 Types of Fasteners Evaluated

Two main types of fasteners are used to assemble supports located along highways to which luminaires, traffic signals and overhead signs are attached. These are (1) anchor bars, most commonly made from low carbon steel but occasionally high-strength steel, and (2) high-strength cap screws. Both types of fasteners are required to be hot-dip galvanized.

Anchor bars used to anchor base plates of pole type structures are normally cast-in-place in concrete foundations. For pole structures along California's highways, two nuts are typically used on each anchor bar, one above and one below the base plate to facilitate erecting and leveling of the pole structures. Once the pole has been leveled, the top nut is currently wrench tightened only. The top of the concrete foundation is normally poured a few inches short of the desired finished grade to allow access to the lower nuts for leveling the pole, and mortar is packed beneath the base plate after leveling has been completed.

Cap screws are used to attach mast or signal arms to the vertical poles of traffic signal and lighting standards. These fasteners are exposed to the outside elements and hence are hot-dip galvanized. They are often subjected to combined loading including tension, shear and bending due to a prying action.

1.3.1 Anchor Bars

Low Carbon (ASTM A307):

Anchor bars which are specified by Caltrans to secure most structures which support luminaires, and all traffic signals and overhead signs to foundations must comply with requirements in the ASTM specification A307.

The most critical loading on these anchor bars is of a cyclic nature caused by wind. The combined loads of tension, shear, and bending due to a prying action of the base plate often act on the bars simultaneously. Caltrans design engineers have felt that the allowable working tensile stress, 14.4 ksi or 0.40 Fy permitted by AASHTO in section 1.4.1(D)(2) of the "Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals"(10) is too conservative for these low carbon steel bars.

High-Strength (ASTM A449):

It is required by Caltrans that anchor bars used for certain luminaire supports, including Caltrans types 30, 31, and 35-20A lighting standards comply with requirements in ASTM specification A449. An allowable working tensile stress of 39.5 ksi (based on the nominal bolt area) is permitted by AASHTO for high-strength A325 bolts having the same properties as the A449 anchor bars previously mentioned, as shown on page 171A in Table 1.7.41C 1 of the "Standard Specifications for Highway Bridges"(9), provided that the combined effects of the prying load and direct tensile load meet certain criteria as specified in Section 1.7.41C(4).

Also, where shear is a substantial part of the combined loading, the following equation from Section 1.3.4(c) of AASHTO, "Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals"(10) is provided:

$$F_v^2 = (f_v)^2 + (kf_t)^2$$

where K = 0.7 for A307 bolts
= 0.375 for A325 bolts where threads are not excluded from the shear plane.

In certain windy locations within California where frequent cyclic loading at moderate to high stress ranges is common, fatigue failures of 7/8-inch and 1-inch- diameter ASTM A449 anchor bars used in foundations of luminaire supports have occurred. High wind loads coupled with the presence of small cracks at the roots of the bar threads, initiated either by unauthorized cold bending of misaligned bars during installation of luminaire supports, stress corrosion, or possibly corrosion fatigue, have probably caused these failures.

1.3.2 High-Strength Cap Screws

Caltrans requires that the cap screws be high strength (ASTM A325) and be tightened 1/3 turn past snug tight. This preload reduces the internal stress range to which cap screw are subjected during cyclic loading and hence extends their fatigue life.

There are inherent problems with the typical mast arm-to-pole connection on lighting standards and traffic signals which can cause cap screw fatigue life to be reduced considerably. The problems may include 1) the mating surfaces of mast arm and pole plates being warped due to the method of welding used to attach the end plate to the mast arm tube, 2) loss of cap screw preload due to compression of irregularities in the zinc coating, 3) a low slip coefficient offered by the unroughened hot-dip galvanized faying surfaces, and 4) lack of lubrication on the cap screw threads. Designers have also been uncertain about the effects of the prying action on fatigue life of these cap screws.

1.4 Scope of Research

An experimental testing program was planned and carried out in order to establish S-N curves and reliable endurance limits for hot-dip galvanized ASTM A307 and A449 anchor bars and ASTM A325 cap screws typically used in structural supports for luminaires, traffic signals, and highway signs.

Anchor Bars:

In the anchor bolt cyclic testing phase, the fatigue life of both high-strength (1-inch diameter A449) and low carbon galvanized steel bars (1 1/4-inch-diameter and 1 3/4-inch-diameter A307) were evaluated by applying sinusodial axial tensile loads at various external stress ranges until failure occurred or 2 million cycles were reached. Parameters considered important in this anchor bar testing project were:

1) stress range based on external loads
2) preload level
3) diameter of anchor bars
4) type of steel
5) stressed length

A total of 95 1-inch-diameter ASTM A449 bars, 58 1 1/4-inch-diameter ASTM A307 bars, and 37 1 3/4-inch-diameter ASTM A307 bars were tested at two different stressed lengths and at various preload levels. Various S-N curves have been drawn from test results.

Cap Screws:

The fatigue lives of both 5/8-inch- and 1-inch-diameter high-strength cap screws were determined through cyclic loading at two different preload levels until failure occurred or 2 million cycles were reached. Parameters considered important included:

1) Stress range based on external loads,
2) preload level,
3) cap screw diameter, and
4) combined loading (tension and prying action).

Since cap screws are often subjected to both tensile forces and a bending or prying action, testing fixtures were designed so that cap screws would be stressed to approximate their operational combined loading. A total of 30 pairs of 5/8-inch-diameter and 25 pairs of 1-inch-diameter cap screws were tested. S-N curves are presented for the two preload conditions tested.

2. CONCLUSIONS

2.1 General Comments

A total of 190 direct tension fatigue tests of anchor bars and 55 fatigue tests of pairs of high-strength cap screws subjected to combined tension and prying action were conducted in this research project in order to evaluate fatigue strength of these fasteners. Various preload conditions, diameters, and lengths of these hot-dip galvanized fasteners were tested to determine their effect on fatigue life.

The most significant variable which was found to be critical in optimizing fatigue life for all fasteners tested was the amount of preload or internal tensile stress present after tightening.

Lubrication of the threads of both anchor bar nuts and cap screw threads proved to be very important in achieving this high tensile stress in the fasteners. The applicaton of dry lubricants which helped minimize galling and reduced torque at various degrees-of-turn of the nuts and capscrew heads, caused a significant increase in the torqued tension at which the fasteners yielded. For the lubricated cap screws, the yield point was from 8 to 20 percent higher than for the unlubricated ones (see graphs D-1 through D-4). Also, the roughness and number of the hot-dip galvanized surfaces being compressed in a joint are also significant factors in achieving and maintaining a desired preload.

2.2 Anchor Bars

The direct tension cyclic fatigue tests of 95 mild steel (ASTM A307) anchor bars of various lengths and sizes and 95 1-inch-diameter high-strength (ASTM A449) anchor bars were performed in order to determine accurate S-N curves for different preload conditions. The following conclusions have been made from the results of the testing:

° Allowable Design Stresses

For the mild steel anchor bars (ASTM A307) it appears that the allowable tensile stress, 14.4 ksi, listed in AASHTO's "Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals"(10) is conservative for systems where double nuts tightened to a snug tight condition are used. Furthermore, no fatigue failures of mild steel anchor bars have been reported by Caltrans maintenance crews. It is evident from S-N curves in Figures B3, B4 and B5 that by tightening the lubricated top nuts to induce tension in the grip length between the double nuts to near the yield point, a substantial increase in fatigue life will result (from two to three times more fatigue cycles for a given stress level). This would allow designers to perhaps increase allowable design stresses, depending on the number and severity of cyclic load anticipated.

For high-strength anchor bars (ASTM A449) with double nuts in a snug tight condition, the allowable tensile stress, 36 ksi, now used by Caltrans appears to be somewhat liberal when compared to the design methods and data from S-N curves obtained for the mild steel anchor bars. For example, considering tensile loading only, the 1 1/4-inch-diameter mild steel anchor bars with double nuts in a snug tight condition and designed using an allowable tensile design stress of 13.5 ksi would be able to withstand over 500,000 cycles at that stress level before failure (see Figures B3 and B4 and Note in Table 1, page 15). On the other hand, the 1-inch-diameter high-strength anchor bars with snug tight double nuts and designed using an allowable design tensile stress of 36 ksi would be able to withstand only 35,000 cycles at that stress range before failure would occur (see Figure B1).

° Effect of Bar Preload on Fatigue Life

The amount of preload applied to and maintained in the fastener body is the most important factor which affects the endurance limit of a fastener. High preloads, near the yield point of the steel, reduce the internal stress range which a fastener body is subjected to during cyclic loading. Although the stress range normally plotted on an S-N curve is based on external load divided by the cross sectional area of a fastener, the real stress range which a fastener experiences is reduced considerably by a large preload.

Of the various anchor bar preload conditions tested in this research, the system currently used by Caltrans, consisting of a top nut nominally tightened to "wrench tight" and a leveling nut located beneath a base plate used on each anchor bar to secure and level a base plate, exhibited the poorest fatigue performance. A considerable improvement in fatigue life was increased from between three and ten times by tightening the top nut 1/3 turn past snug tight (see Appendix B for S-N curves). For 1-inch-diameter A449 anchor bars, fatigue life was doubled by tightening the top nut 1/3 turn past snug tight.

The longest fatigue lives for the anchor bars were obtained where bars with single nuts were preloaded to yield. This represents a condition where no leveling nut is present and the anchor bar is not bonded to the concrete for its full length. Infinite fatigue lives were obtained for all bars tested at stress ranges at or near the guaranteed yield point of the steel in the bar. The practice of fully preloading an unbonded anchor bar is not currently practical because of 1) the high torques which would be required to be applied on site to achieve an anchor bar stress near the yield point, 2) the continuing need to provide leveling nuts for plumbing most poles and 3) the possible problem of a weak grout pad under the base plate not being able to carry high compressive forces transmitted by unbonded and fully preloaded anchor bars with single nuts.

° Effect of Steel Type on Fatigue Life

For anchor bars with double nuts and subjected to cyclic loads with an upper stress level at or below the yield point of A307 steel, the fatigue life of the ASTM A307 steel bars is equal to or better than that of the ASTM A449 steel bars (as shown in Figures B15, B16, B18, B19, and B21). Thus, if the number of cycles of a given stress range shown in these figures is expected to exceed approximately 50,000, the mild steel bars can be expected to have longer fatigue lives than the high-strength anchor bars.

For anchor bars with single nuts and preloaded over their full length, however, the high-strength steel bars out perform the mild steel bars, and appear to have infinite fatigue lives above the guaranteed yield stress level of the mild steel bars, as shown in Figures B17 and B20.

° Effect of Bar Length on Fatigue Life

The effects of variations in the lengths of the anchor bars tested in this research on fatigue life were negligible.

° Effect of Diameter on Fatigue Life

The effect of variations in the diameter of the 1 1/4-inch- and 1 3/4-inch-diameter ASTM A307 anchor bars tested on fatigue life were negligible.

2.3 Cap Screws

A total of 55 fatigue tests of pairs of both 5/8-inch-diameter x 1 3/4-inch and 1-inch-diameter x 2 1/2-inch high-strength cap screws were performed to develop accurate S-N curves and evaluate the effects of preload and prying action on typical mast arm-to-pole joints. All A36 steel used for joint material and all cap screws tested were hot-dip galvanized. The following comments are conclusions based on results on this research.

° Allowable Design Stresses

The allowable tensile stress of 36 ksi currently used by Caltrans designers to determine required sizes of high-strength cap screws which are used to attach mast arms to pole shafts appears to be somewhat conservative. This judgement is based on fatigue results in S-N plots shown in Figure C4, as well as the allowable tensile stress of 39.5 ksi on the nominal bolt area currently permitted by AASHTO.

° Effect of Preloading Cap Screws

Both the 5/8-inch-diameter and 1-inch-diameter lubricated ASTM A325 cap screws tested in cyclic loading with combined prying action and tension performed well when tightened to 1/3 turn past snug tight currently required by Caltrans. Cap screws tightened to that point, which exceeded the minimum specified yield point of both cap screw sizes tested, exhibited fatigue lives of 500,000 cycles or better when cycled using a stress range of 50 ksi, as shown in Figure C4. The fatigue lives at that stress range for the cap screws tightened to the snug tight condition only are between twenty to fifty times smaller, as indicated by the S-N curves shown in Figures C1 and C2.

° Effect of Prying Action on Fatigue Life

With the joint stiffnesses and geometries tested in this research, the effect of prying action on the cap screws tightened to 1/3 turn past snug tight appears to be small. This is apparent when the S-N curves in Figures C4, B1 and B2 are compared.

3. RECOMMENDATIONS AND IMPLEMENTATION

Based on the findings and conclusions of this research, the following recommendations are made:

3.1 Anchor Bars

- For design purposes, use the appropriate S-N curves developed in this research and presented in Appendix B (Figures B1 through B23) for anchor bars and in Appendix C (Figures C1 through C4) for high-strength cap screws.

- Select proper allowable design stress based on number of cycles of maximum load expected, desired safety factor, and a cumulative usage assessment based on the desired service life of the traffic signal, lighting standard, or sign structure. See the following Table 1 for a comparison of the actual number of cycles to failure for various maximum stress levels shown. Determination of satisfactory fatigue life or performance may require a complex dynamic analysis utilizing a computer program such as WEFFLS as previously done by Mechanics Research Inc.(6).

- Continue to use anchor bars with a two-nut system. Tighten the top nut on all new anchorage systems utilizing high strength anchor bars and those using mild steel anchor bars to and including 1 1/4-inch-diameter to or near the guaranteed minimum yield point of the fastener. On hot-dip galvanized fasteners, this may be most easily done by the turn-of-nut method. The degrees of turn required to achieve proper preload in the section of anchor bar between the top and leveling nuts will vary

Table 1. Cycles to failure for various levels of maximum applied stress.

FASTENER TYPE	MAXIMUM EXTERNALLY APPLIED STRESS(a)	CYCLES TO FAILURE FOR:			
ANCHOR BARS	ksi	DOUBLE NUTS SNUG TIGHT	DOUBLE NUTS 1/3 TURN PAST SNUG TIGHT	SINGLE NUT BAR PRELOAD =.55Fy min.	SINGLE NUT, BAR PRELOAD =1.0Fy min.
ASTM A449 1"Ø	36(b) (Caltrans Structural Design)	35,000	60,000	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles
	1.4(c)x36 (50.4)	15,500	25,000	640,000	exceeds 2,000,000 cycles
	39.5(d)(51.2) (AASHTO Bridge Specs.)	14,500	24,000	580,000	exceeds 2,000,000 cycles
ASTM A307 1 1/4"Ø	13.5(e) (AASHTO Bridge Specs.)	640,000	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles
	14.4 (AASHTO Tech. Committee Draft)	500,000	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles
	1.4(c)x13.5 (18.9)	190,000	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles
ASTM A307 1 3/4"Ø	13.5(e) (AASHTO Bridge Specs.)	940,000	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles
	14.4 (AASHTO Tech. Committee Draft)	740,000	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles
	1.4(c)x13.5 (18.9)	275,000	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles	exceeds 2,000,000 cycles

(n) See footnotes on page 15 for an explanation.

Table 1. Continued....

FASTENER TYPE	MAXIMUM EXTERNALLY APPLIED STRESS (a)	CYCLES TO FAILURE FOR:	
ASTM A325 CAP SCREWS	ksi	HEAD TURNED SNUG TIGHT	HEAD TURNED 1/3 TURN PAST SNUG TIGHT
5/8"Øx1 3/4"	36 (b) (Caltrans Structural Design)	115,000	exceeds 2,000,000 cycles
	1.4 (c) x36 (50.4)	22,000	640,000
	39.5 (d) (53.6) (AASHTO Bridge Specs.)	17,000	370,000
1"Øx2 1/2"	36 (b) (Caltrans Structural Design)	20,000	exceeds 2,000,000 cycles
	1.4 (c) x36 (50.4)	7,400	210,000
	39.5 (d) (51.2) (AASHTO Bridge Specs.)	6,200	200,000

Note: Values shown in the "Cycles to Failure" column in Table 1 are obtained by first selecting the appropriate S-N curve shown in Appendix B, then drawing a line parallel to and below the original S-N curve through the minimum data point of the plotted S-N curve. Finally, the appropriate cycles to failure may be read for the desired stress range from the lower S-N curve.

ⓐ Based on stress area of bolt except as noted.

ⓑ Allowable design stress currently used by Caltrans structural Design.

ⓒ Allowable unit stress increase as shown in Table 1.2.6 of AASHTO's "Standard Specification for Structural Supports for Highway Signs, Luminaires and Traffic Signals." This factor is used by Caltrans Structural Design and applied to all cap screws and anchor bars used in traffic signals and lighting standards.

ⓓ Based on nominal area of the body of the bolt.

ⓔ Based on thread root area.

depending on grip length, thread pitch, bar diameter, the number and roughness of galvanized surfaces being compressed, and joint stiffness. Require that all nuts for anchor bars 1 1/4 inches in diameter and smaller be lubricated with a satisfactory dry lubricant. All anchor bars 1 1/2 inches in diameter and larger should be lubricated and tightened to a minimum of 250 ft lbs of torque, but not past the yield point of the fastener.

- Lubricate and tighten top nuts of existing high-strength anchor bars close to their yield point on signals and lighting standards in areas subject to heavy wind loading. This should be done as time and money permit.

3.2 Cap Screws

- Continue to lubricate and preload cap screws fully to their yield point to maximize their fatigue life. To achieve yield for 5/8, 3/4 and 1, and 1 1/4-inch-diameter lubricated cap screws with various grip lengths, use turns of cap screw head shown in the following Table 2:

Table 2. Turn-of-cap screw head past snug tight required to preload high-strength lubricated cap screws.

Cap Screw Diameter, Inch	Grip Length, Inches	Turn-of-Nut Cap Screw Head Past Snug Tight Required to Reach Yield
5/8	0.75	1/4
3/4	1.0	1/4
1	1.0	1/3
1 1/4	1 1/4, 1 1/2	1/3

3.3 Future Recommended Research

It is further recommended that the following items be investigated in the future as time, money, and manpower permit:

- Where long fatigue life is required, develop a feasible method to preload the entire length of an unbonded anchor bar and still maintain the capability of leveling the structure.

- Determine the effect of various suitable lubricants on the tension versus turn-of-nut relationships of various galvanized anchor bars and cap screws.

- Determine a wind load history of large lighting standards in extremely gusty windy areas throughout California. This might be done by instrumenting and monitoring anchor bars to determine internal stress levels, the number of cycles of tensile loads, and wind velocity.

- Determine and verify the effects of prying action on anchor bars used to anchor base plates on traffic signals and lighting standards.

4. DESCRIPTION OF EXPERIMENTAL PROGRAM

4.1 Testing Program - General Discussion

Testing consisted of continuous cyclic loading of hot-dip galvanized threaded anchor bars and cap screws to failure. The specimens were subjected to varying external loads at different preload conditions to determine their fatigue life. Anchor bars were cycled in tension only, whereas cap screws were loaded with combined tension and bending (prying action). All of the testing was done by the Structural Materials Research Unit of the Structural Materials Branch of the Transportation Laboratory in Sacramento, California.

4.2 Test Specimens

4.2.1 General Discussion

In this research project, anchor bars made of two different types of steel, mild steel (ASTM A307) and high-strength steel (ASTM A449), were tested and are representative of anchor bars currently used by Caltrans. Three different diameters of bars were selected, 1-inch (ASTM A449), 1 1/4-inch and 1 3/4-inch (ASTM A307). These bar sizes are commonly used to anchor lighting standards and sign and signal poles. Appropriate washers and nuts were selected for each bar size. All bar specimens were threaded at both ends and were tested so that two different tests were conducted simultaneously, one at each end of the bar. Results of the bar end which failed first were recorded.

Two sizes of A325 cap screws were tested: 5/8-inch- and 1-inch-diameter. These cap screws are representative of those currently used by Caltrans to attach luminaire and signal arms to tops of vertical pole shafts.

All bars, nuts, washers and cap screws used in this fatigue study were hot-dip galvanized in accordance with the requirements of ASTM Specification 153, Class C. A summary of the various anchor bars and cap screws tested in this research project is presented in Table 3. The following information explains in more detail specific requirements for the test specimens.

Table 3. Sizes of specimens tested.

	Anchor Bars			Cap Screws	
ASTM Spec.	A449	A307	A307	A325	A325
Diameter	1"	1 1/4"	1 3/4"	5/8"	1"
Length	16" 24"	19" 46"	27"	1 3/4"	2 1/2"

4.2.2 <u>Anchor Bars</u>

4.2.2.1 Types of Bars

Two types of anchor bars currently used by Caltrans were tested. These included (1) hot-dip galvanized high-strength anchor bars typically used for Type 30 and 31 lighting standards and meeting the requirements of ASTM Specification A449, and (2) hot-dip galvanized mild steel anchor bars meeting the requirements of ASTM Specification A307. Both mechanical and chemical properties of anchor bar samples of each length and diameter were determined prior to conducting any cyclic tests to verify conformance to the appropriate ASTM specifications. Each of the bar types was manufactured from one lot of steel. The results of these tests, together with the required values from appropriate ASTM specifications, are shown in Tables 4, 5 and 6.

Table 4. Properties of 1-inch-diameter A449 anchor bars tested.

PROPERTY	TEST RESULTS 16-INCH-LONG BARS	TEST RESULTS 24-INCH-LONG BARS	SPECIFICATION LIMITS
Proof Load by Yield Strength Method (0.2% offset), psi	greater than 92,000		92,000 min.
Tensile Strength, psi	144,600	136,100	120,000 min.
Chemical Elements, %			
Carbon	0.45	0.48	0.25-0.58
Manganese	1.43	1.45	0.57 min.
Phosphorus	0.01	0.01	0.048 max.
Sulfur	0.021	0.021	0.058 max.
Hardness	Rockwell C 25	Rockwell C 26	Rockwell C 25-34 Brinell 255-321
Number of Threads per inch	8	8	8
Thread Pitch Diameter, inches	0.915	0.915	0.9168 max. 0.9100 min.
Galvanized Coating Weight, oz/ft^2	2.53	2.54	1.25

Table 5. Properties of 1 1/4-inch-diameter A307 anchor bars tested.

PROPERTY	TEST RESULTS		MILL TEST REPORT	SPECIFICATION LIMITS
	19-INCH-LONG BARS	46-INCH-LONG BARS		
Yield Strength, psi	42,700	41,600	43,820	36,000 min.
Tensile Strength, psi	68,000	68,300	66,610	58,000-80,000
Elongation in 8 inches, %	37.0*	28.6	31.0	20 min.
Reduction of Area, %	63.2	60.0	-	-
Chemical Elements, %				
Carbon	0.21	0.21	0.20	0.27 max.
Manganese	0.78	0.77	0.75	0.60-0.90
Phosphorus	0.012	0.010	0.007	0.04 max.
Sulfur	0.031	0.035	0.034	0.05 max.
Number of Threads per inch	7	7	-	7
Thread Pitch Diameter, inches	1.137	1.137	-	1.1550 max. 1.1476 min.
Galvanized Coating Weight, oz/ft^2	2.29	2.76	-	1.25 min.

*2-inch elongation 23% minimum

Table 6. Properties of 1 3/4-inch-diameter x 27-inch-long A307 anchor bars tested.

PROPERTY	TEST RESULTS	SPECIFICATION LIMIT
Yield Strength, psi	58,067	36,000 min.
Tensile Strength, psi	73,767	58,000-80,000
Elongation in 2 inches, %	28	23 min.
Chemical Elements, %		
Carbon	0.24	0.28 max.
Manganese	0.86	0.60-0.90
Phosphorus	0.013	0.04 max.
Sulfur	0.044	0.05 max.
Silicon	0.10	
Number of Threads per inch	5	5
Thread Pitch Diameter, inches	1.621	1.6085-1.6484
Major Diameter, inches	1.746	1.1650-1.7783
Galvanized Coating Weight, oz/ft^2	1.75	1.25 min.

Only one diameter of high-strength anchor bar, one-inch, was tested. Two different lengths, 16-inch and 24-inch, of this high-strength bar were tested. The shorter 16-inch-long bars tested using double nuts at each end of the bar, had a 10-inch distance (representing 10 bar diameters of embedment length) between fixtures. Tests conducted using this shorter bar with double nuts approximated existing conditions where the anchor bars are bonded in the concrete and the full strength of the anchor bar is developed within a depth of 10 bar diameters. The 24-inch-long bars having single nuts on each end of the bar were tested to determine if by unbonding and prestressing the entire existing bar length, a substantial increase in the fatigue life would result.

In order to plot the various S-N curves, fifty-six 16-inch-long and thirty-nine 24-inch-long A449 anchor bars were tested by cycling with a direct tension load. Six inches on each end of all 1-inch-diameter high--stength anchor bars were threaded with Unified National Coarse Threads having a Class 2A tolerance. All bars were hot-dip galvanized according to ASTM Specification A153. All bar ends were machined flat to facilitate measuring changes in length with a specially built "C" caliper having a dial indicator to indirectly determine preload levels.

Two different diameters of anchor bars complying with requirements ASTM specification A 307 were tested: 1 1/4-inch and 1 3/4-inch. The reason for testing these two diameters was to determine what effect diameter has on the fatigue life for similar stress ranges. Two different bar lengths were tested in the 1 1/4-inch-diameter anchor bars. The shorter of the two, a 19-inch-long bar represents the existing condition where the anchor bar is cast-in-place in concrete and the full bar load is developed by bond in the top 12.5 inches (10 bar diameters). The 46-inch-long bar represents the typical standard anchor bar length unbonded. A total of twenty-nine 19-inch-long and twenty-nine 46-inch-long 1 1/4-inch- diameter A307 anchor bars were used in the cyclic tests.

Thirty-seven 1 3/4-inch diameter A307 anchor bars were tested in one length only - 27 inches - because of limited time and funding. Again, this represents the condition were only the top 10 bar diameters is stressed.

Eight inches on each end of these anchor bars were threaded with Unified National Coarse Threads having a Class 2A tolerance. As before, the ends of the bars were machined flat to facilitate measuring the changes in length at various preload levels with a "C" caliper and dial indicator.

All anchor bars were tested using two different nut arrangements: (1) double nuts on each end of the bars, representing the current practice of using a leveling nut beneath the base plate, and (2) a single nut on each end of the bars representing an unbonded fully preloaded condition. Grip lengths of the various systems tested are shown in Table 7. Because bases of fixtures designed for laboratory cyclic testing were extremely rigid and hence thick, grip lengths used for anchor bars having double nuts are somewhat longer than those found in actual base plate assemblies shown in Figures D1 through D7.

Table 7. Anchor bar grip lengths.

NUMBER OF NUTS	PRELOAD CONDITION	ANCHOR BAR TYPES				
		ASTM A449		ASTM A307		
		1"Øx16"	1"Øx24"	1 1/4"Øx19"	1 1/4"Øx46"	1 3/4"Øx27
Double Nuts	Snug Tight	1.8"	1.8"	1.8"	1.8"	2.2"
	1/3 Turn Past Snug Tight	1.8"	1.8"	1.8"	1.8"	2.2"
Single Nut	55% of Fy	13.2"	21.2"	15.7"	41.2"	21.4"
	100% of Fy	13.2"	21.2"	15.7"	41.2"	21.4"

4.2.2.2 Nuts

Two grades of nuts were used in this test program. The nuts used with all 1-inch-diameter A449 anchor bars were heavy hex grade 2H nuts meeting the requirements of ASTM Specification A194. Nuts on all 1 1/4-inch-diameter, and the 1 3/4-inch-diameter A307 anchor bars were Grade A nuts meeting the requirements of ASTM Specification A563. The results of the preliminary tests to determine the physical properties of the nuts and how they compare to the specifications are shown in Table 8. The nuts were tapped oversize in accordance with Section 75-1.05 of the 1981 Caltrans Standard Specifications to accommodate the galvanizing on the anchor bars.

Table 8. Properties of hot-dip galvanized nuts.

PROPERTY	NUTS FOR 1"Ø A449 BARS	SPECIFI-CATION LIMIT	NUTS FOR 1 1/4"ØA307 BARS	SPECIFI-CATION LIMIT	NUTS FOR 1 3/4"ØA307 BARS	SPECIFI-CATION LIMIT
Grade/Style	2H/heavy hex	-	A/hex	-	A/heavy hex	-
Proof Load, lbs	passed	106,000 min.	passed	87,000 min.	Not tested - hardness measurement used	
Chemical Elements, %						
Carbon	0.54	0.40 min.	0.36	0.58 max.	0.52	0.58 max.
Phosphorus	0.01	0.40 max.	0.007	0.13 max.	0.13	0.13 max
Sulfur	0.034	0.050 max.	-	-	-	-
Thread Pitch Diameter, inches	less than 0.9506	0.9506 max.	less than 1.1998	1.1998 max.	less than 1.6647	1.6647 max.
Number of Threads per inch	8 UNC	8 UNC	7 UNC	7 UNC	5 UNC	5 UNC
Distance Across Flats - inches	1.608	1.575 min. 1.625 max.	1.954	1.938 min. 2.000 max	2.685	2.662 min. 2.750 max
Distance Across Corners, inches	1.838	1.796 min. 1.876 max.	2.236	2.209 min. 2.309 max.	3.073	3.035 min. 3.175 max.
Thickness, inches	1.000	0.956 min. 1.012 max	1.219	1.187 min. 1.251 max.	1.768	1.679 min. 1.759 max.
Hardness	Rockwell C29 Brinell 311	Rockwell C24-38 Brinell 248-352	Rockwell C23 Brinell 104	Rockwell B68-C32 Brinell 116-302	Rockwell B90	Rockwell B68-C32
Galvanized Coating Weight, oz/ft^2	1.44	1.25 min.	2.49	1.25 min.	6.67	1.25 min.

4.2.2.3 Washers

As shown in Table 9, appropriate galvanized washers were used in the cyclic load tests. All washers used in anchor bar testing met the dimensional requirements of the American National Standards for Plain Washers. The washers used with the 1-inch-diameter A449 anchor bars also met the requirements of ASTM Specification F436.

Table 9. Properties of hot-dip galvanized washers.

	PROPERTY FOR 1"ØA449 BARS	SPECIFI-CATION LIMIT	PROPERTY FOR 1 1/4"ØA307 BARS	SPECIFI-CATION LIMIT	PROPERTY FOR 1 3/4"ØA307 BARS	SPECIFI-CATION LIMIT
Outside Diameter, inches	2.007	2.031 max. 1.969 min.	3.000	3.030 max. 2.993 min	4.027	4.045 max. 3.990 min.
Inside Diameter, inches	1.108	1.156 max. 1.125 min.	1.373	1.405 max. 1.368 min.	1.889	1.920 max. 1.865 min.
Thickness, inches	0.155	0.177 max. 0.136 min.	0.170	0.192 max. 0.136 min.	0.196	0.213 max. 0.153 min.
Galvanizing Coating Wt, oz/ft^2	2.89	1.25 min.	1.89	1.25 min.	1.78	1.25 min.
Hardness	Rockwell C43	Rockwell C26-45				
Chemical Elements, %						
Phosphorus	0.01	0.050 max.				
Sulfur	.021	0.060 max.				

4.2.3 Cap Screws

All the cap screws tested met the requirement of ASTM Specification A325. Two sizes of cap screws were fatigue tested: 5/8-inch-diameter x 1 3/4 inches long and 1-inch-diameter x 2 1/2 inches long. The results of the compliance tests to determine the physical properties of the cap screws are shown in Table 10. The cap screws were modified by machining both ends flat to facilitate measuring lengths with a "C" caliper and dial indicator.

Table 10. Cap screw properties.

PROPERTY	TEST RESULTS FOR 5/8"Ø	SPECIFI-CATION LIMIT	TEST RESULTS FOR 1"Ø	SPECIFI-CATION LIMIT
Proof Load, Alt.Method, psi	-	92,000 min.	-	92,000 min.
Tensile Strength, psi	-	120,000 min.	152,800	120,000 min.
Chemical Elements, %				
Carbon	0.38	0.27 min.	0.38	0.27 min.
Manganese	0.73	0.47 min.	0.71	0.47 min.
Phosphorus	0.017	0.048 max.	0.024	0.048 max.
Sulfur	0.014	0.058 max.	0.021	0.058 max.
Hardness	Rc-30	Rc-24 to 35 Brin.-248 to 331	Brin.-273	Rc-24 to 35 Brin.-248 to 331
Number of Threads per inch	11	11	8	8

4.3 Testing Equipment

4.3.1 Testing Machines Used

In order to accommodate the various lengths and sizes of anchor bars and cap screws, three universal testing machines were used for applying cyclic loads. The smallest of the three machines used, an MTS electro-hydraulic testing machine, has a dynamic load capacity of 50 kips. It was used to test the 1-inch-diameter high strength anchor bars, the 5/8-inch-diameter cap screws and some of the 1-inch-diameter cap screws. The medium sized testing machine, whose special load frame was designed and constructed at the Caltrans Transportation Laboratory to accommodate long anchor bars, has a 110 kip dynamic capacity. It was used to test the 1 1/4-inch and 1 3/4-inch-diameter anchor bars. The largest testing machine, also an MTS, has a dynamic load capacity of 500 kips, and was used to test some of the 1-inch-diameter cap screws.

4.3.2 Fixtures

4.3.2.1 Anchor Bar Load Frames

Special rectangular fixtures were designed and constructed to withstand cyclic loading applied to the various lengths and diameters of anchor bars tested. One set of fixtures was used for the 1-inch-diameter anchor bars and then modified and reused for the 1 1/4-inch-diameter anchor bars. A second set was constructed for the 1 3/4-inch-diameter anchor bars.

Both sets of fixtures are similar; the set used to test 1 1/4-inch-diameter anchor bars is shown in Figure 1.

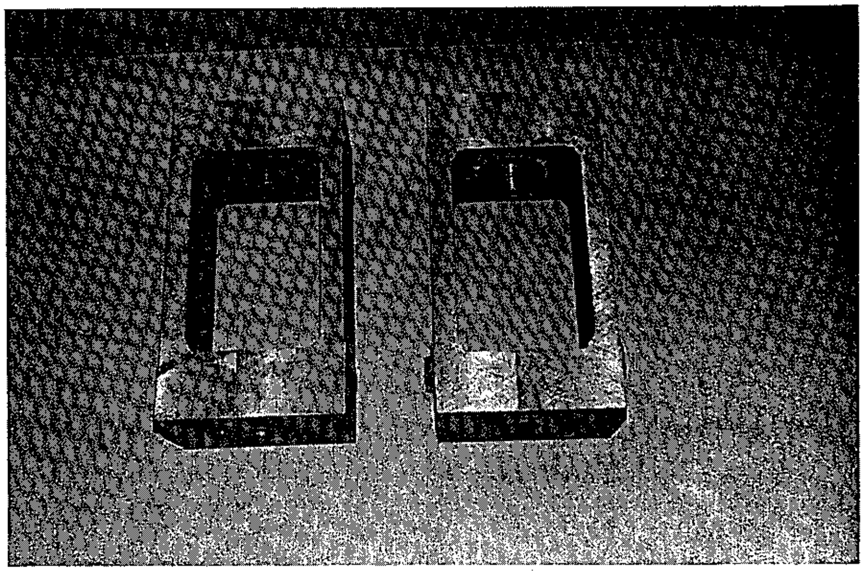


Figure 1. Test fixtures used to cycle the 1 1/4-inch-diameter mild steel anchor bars.

Steel preload sleeves were made in segments and were used to test the preloaded 1-inch-diameter, 1 1/4-inch-diameter and 1 3/4-inch-diameter anchor bars having single nuts on each end. The sleeves were cylindrical in shape with a hole in the center for the bars to go through. They were of different lengths and dimensions so as to accommodate the different anchor bar lengths and diameters tested (see Figure 2).

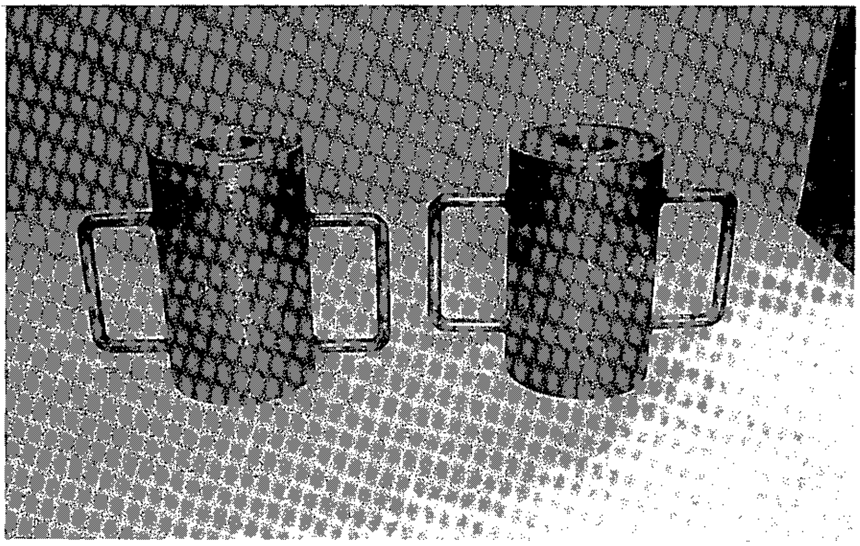


Figure 2. Steel sleeves used for preloading the single nutted 1 3/4-inch-diameter anchor bars.

4.3.2.2 Cap Screw Test Fixtures

Two test fixtures were designed and constructed to test the cap screws - one for the 5/8-inch-diameter cap screws and one for the 1-inch-diameter cap screws (see Figure 3).

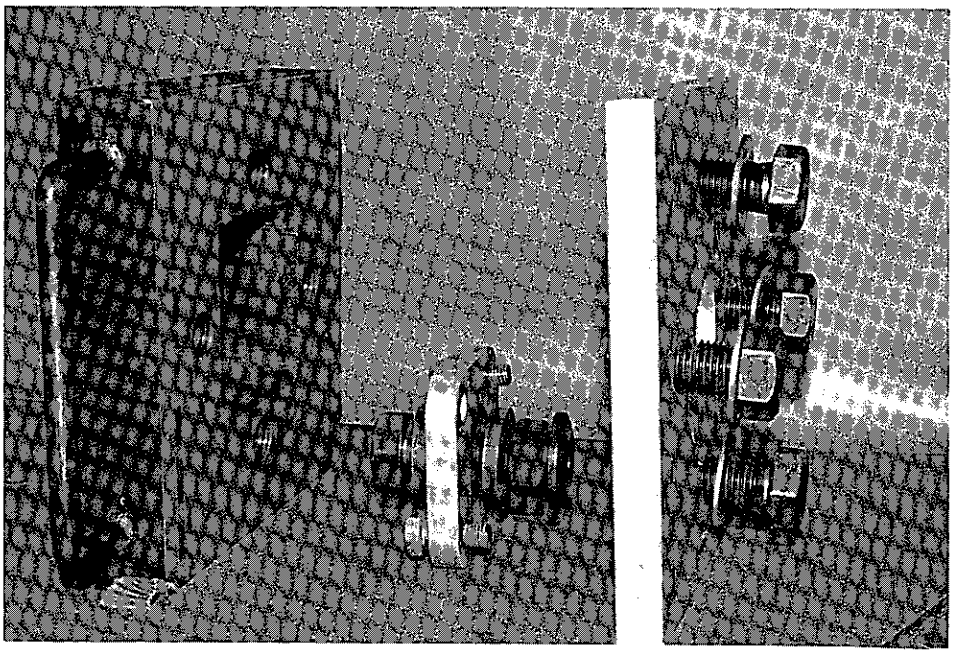


Figure 3. Testing fixture used to cycle pairs of 1-inch-diameter cap screws.

4.3.3 Length Measurement

Special calipers were constructed in order to accurately measure lengths of anchor bar and cap screw specimens during cyclic testing. The "C" frame calipers used were of various sizes to accommodate the different lengths of anchor bars tested and were constructed utilizing a dial indicator attached to one end readable to the nearest 0.0001 inch.

Typical "C" frame calipers are shown in Figures 4 and 5.

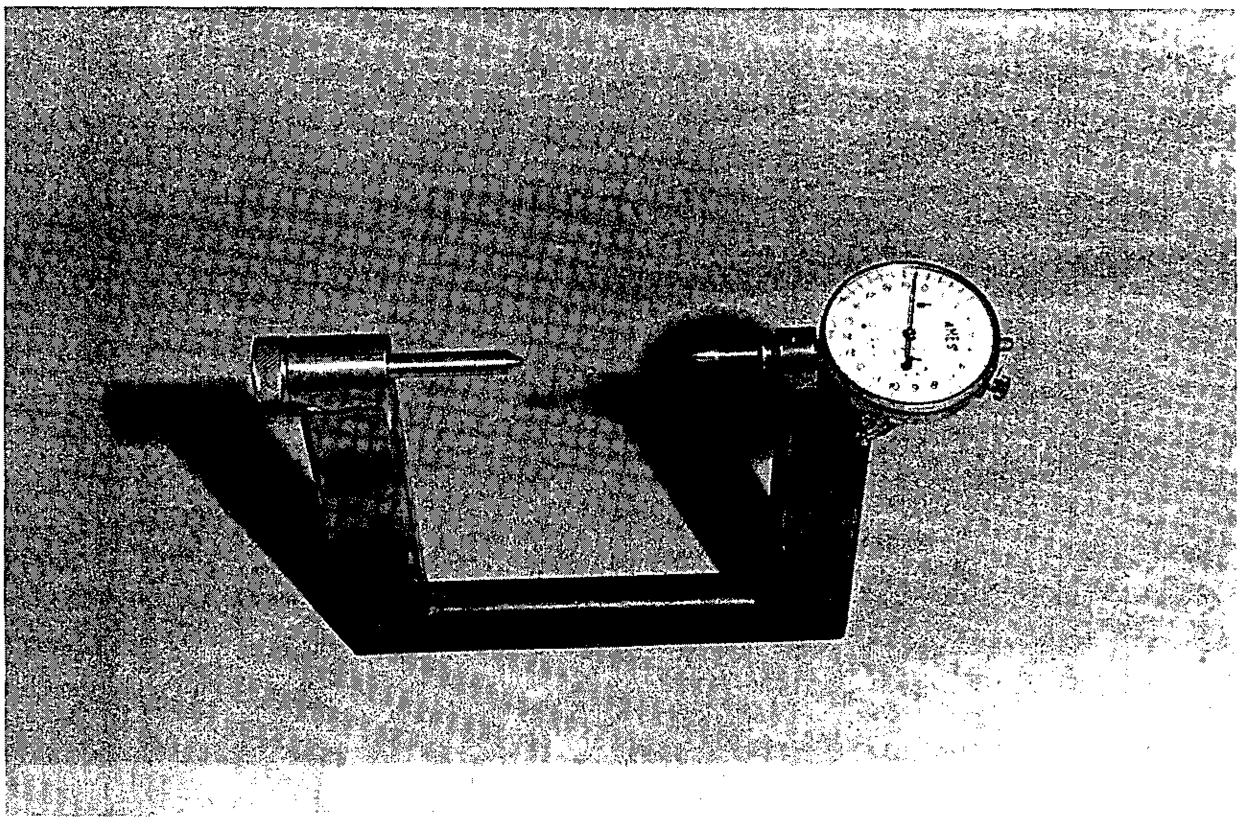


Figure 4. Typical "C" frame caliper for measuring cap screw lengths.

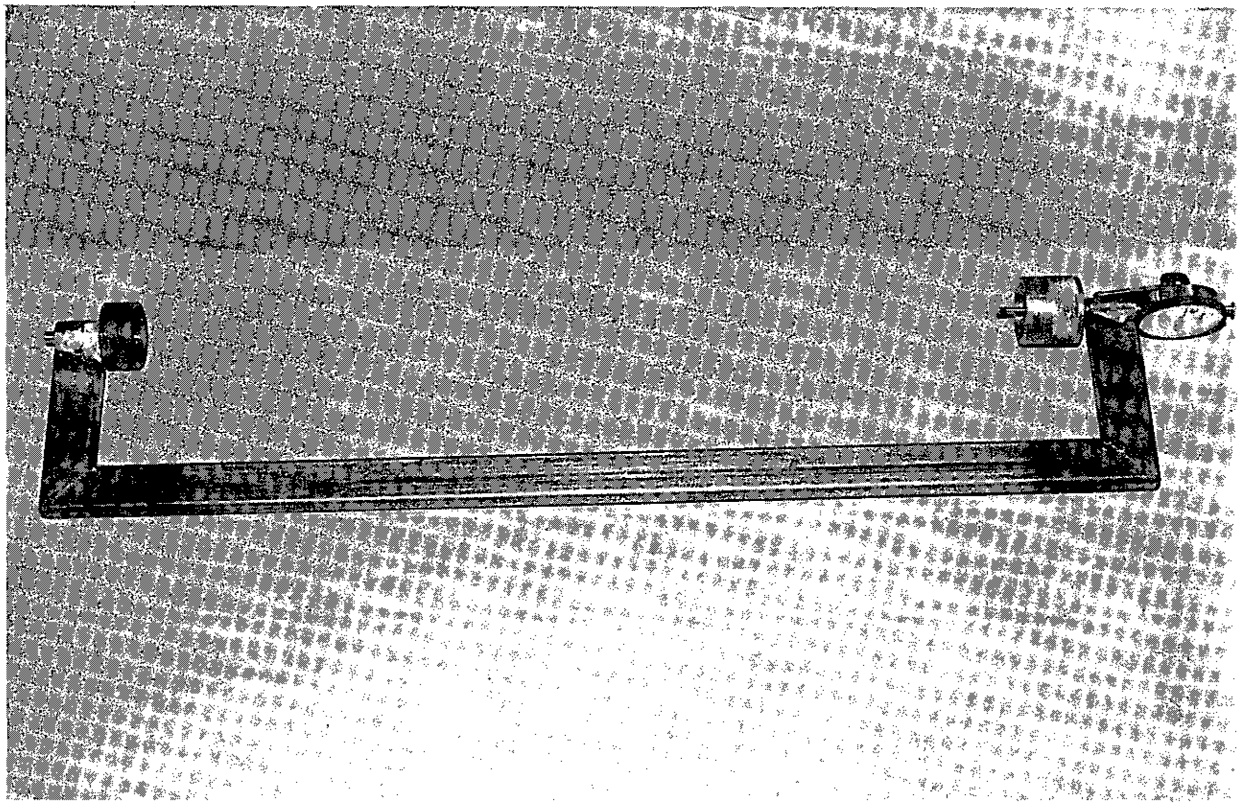


Figure 5. Typical "C" frame caliper for measuring anchor bar lengths.

4.4 Test Procedures

4.4.1 Anchor Bars

4.4.1.1 Mounting Setup

Anchor bars having two different nut arrangements were tested. These were (1) anchor bars having double nuts, representing the system currently used by Caltrans with a leveling nut and outer (top) nut on each bar end, and (2) single nuts representing a system where a full unbonded bar length could be preloaded.

The testing setups for anchor bars with double nuts and preloaded single nuts are shown in Figure 6.

Mounting anchor bars with the double nut system was accomplished by installing a leveling nut and a washer on each end of the bar, then positioning the bar vertically in the testing machine and adjusting the leveling nuts on the bar threads so as to equalize the amount of tensioned threads on each end of bar. The proper and consistent amount of space between the bases of the upper and lower test fixtures was adjusted with these leveling nuts, also. The outer nuts on each end of the bar were then tightened with a torque wrench to either the snug tight condition or to the 1/3 turn past snug tight condition, while holding the leveling nuts with an open-end wrench. This tensioned only the short length of threaded bar between the leveling and outer nut. Prior to installation of the bars, the length of a control bar was measured and recorded as well as the overall test bar length. Frequent length measurements during the nut tightening operation were made in order to monitor bar elongation.

Anchor bars with single nuts were installed differently, using cylindrical steel sleeve spacers between the fixtures so that the entire bar length between the nuts could be preloaded.

Again the length of a control bar was measured along with the actual length of the unloaded test bar. Length changes of the test bar were monitored during the preloading of the test bar to insure correct preload, and during the cyclic loading to determine change in bar length.

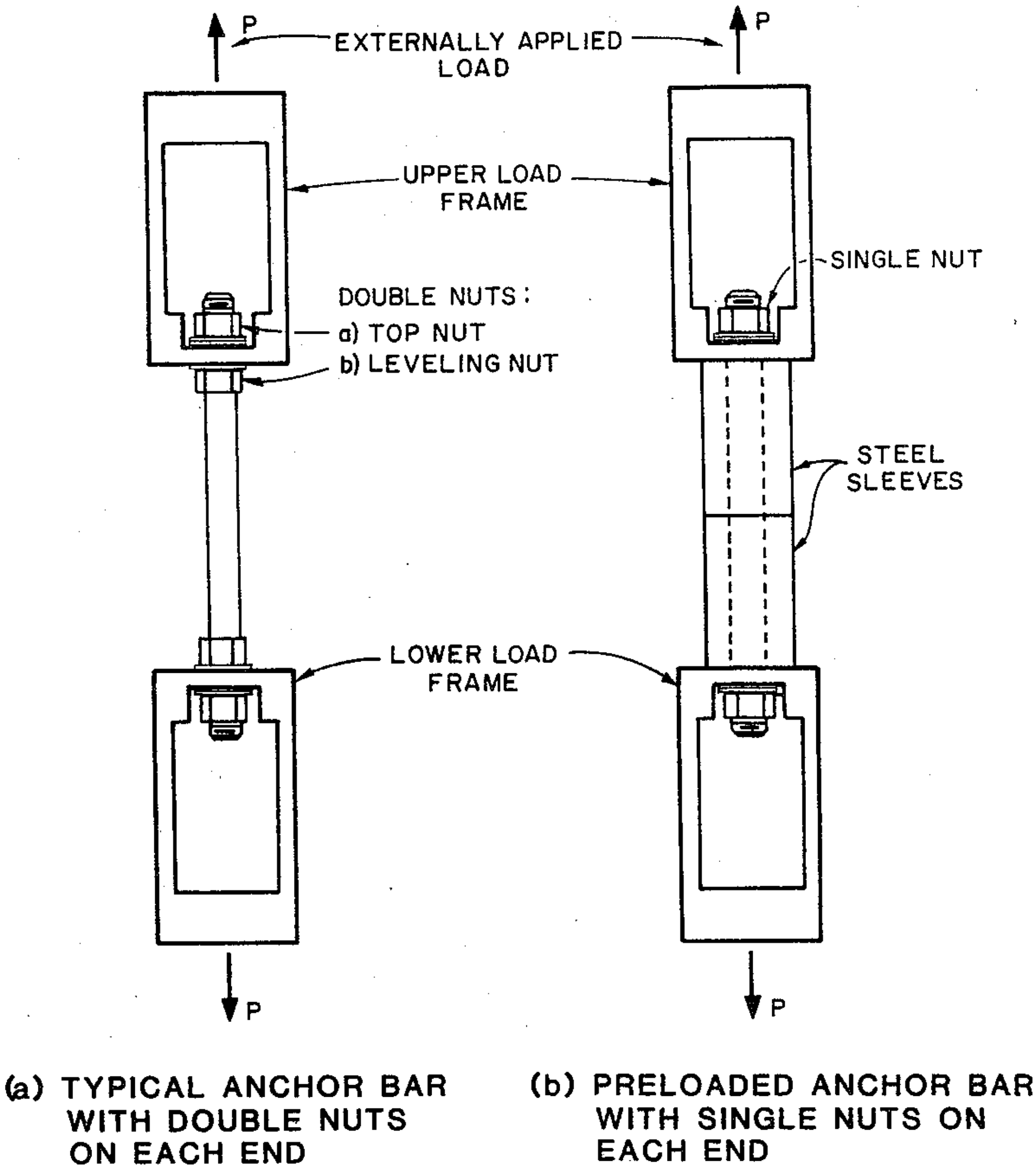


Figure 6. Cyclic testing setup for (a) anchor bars with double nuts and (b) preloaded anchor bars with single nuts.

Prior to assembling anchor bars, nuts and washers in the testing machine, the nuts used on the A307 anchor bars were lubricated to prevent galling of the zinc coating. The lubricant used was Johnson's Wax-Plate 15. A solution of 5 parts of water to 1 part of Johnson's Wax-Plate 15 was used for lubrication. At the start of this testing, the nut manufacturer was using a Daubert Chemical Company lubricant, X-185, but subsequently changed to the Johnson's Wax-Plate 15. Limited testing of these two lubricants showed that there was no significant difference between the two in the coefficient of friction obtained on the threaded surfaces.

4.4.1.2 Determination of Preloads

It was first necessary to develop a relationship between torqued bolt tension and elongation prior to preloading the anchor bars. Tension-elongation curves for the three bar diameters and various lengths were drawn and are shown in Appendix D, Figures D5 through D12. When using the preload sleeves, the anchor bar preloads used were 55% and 100% of the guaranteed yield strength of the anchor bars. From the bolt tension-elongation curves developed, the elongation values were determined for the desired preload and then the anchor bar nuts were tightened until the desired value was reached.

When fatigue tests were conducted using double nuts on the anchor bars, the test fixture base plate was compressed between the inner (leveling) nuts of the anchor bars and the outer nuts. The outer nuts were tightened to either a snug tight condition (100 ft-lbs) or 1/3 of a turn past snug tight.

4.4.1.3 Stress Ranges

The external loads were applied with a sinusoidal cyclic pattern to simulate wind loadings. Each of the external loads was based on a stress range that was a percentage of the guaranteed yield stress. These ranges were 0-100%, 0-83%, 0-67%, 0-33% and 0-10%. The upper and lower levels of these stress ranges were increased by 500 pounds because of limitations imposed by the testing machines.

In Table 11, a loading summary is shown for the different preloads and external loads used for testing the anchor bars and cap screws. Additional cyclic testing at different external load levels was done for some of the anchor bars to facilitate plotting S-N curves.

Table 11. Loading Summary

FASTENER TYPE		CAP SCREWS		ANCHOR BARS		
APPROPRIATE ASTM SPECIFICATION		ASTM A325		ASTM A449	ASTM A307	
DIMENSIONS OF FASTENERS TESTED	Thread Lengths	1 3/8 inches	1 3/4 inches	6 inches both ends	8 inches both ends	8 inches both ends
	Diameter and Length	5/8"Ø x 1 3/4"	1"Ø x 2 1/2"	1"Ø x 16" 1"Ø x 24"	1 1/4"Ø x 19" 1 1/4"Ø x 46"	1 3/4"Ø x 27"
USE		Luminaire Arm-to-Pole Connection	Signal Arm-to-Pole Connection	Anchor Bars For Lighting Standards	Anchor Bars For Traffic Signal and Lighting Standards	
APPROPRIATE REFERENCE PAGES IN CALTRANS 1981 STANDARD PLANS		206, 207	212, 213, 214, 215	209, 210	212, 213, 214, 217, 218	214, 215, 218, 219, 220
STEEL PROPERTIES	Tensile Stress Area Allowable Unit Stress, Tension	0.226 in^2 36,000 psi	0.606 in^2 36,000 psi	0.606 in^2 36,000 psi	0.969 in^2 13,500 psi	1.90 in^2 13,500 psi
	Allowable Design Strength 1.4 x Unit Stress x Tensile Stress Area	11.39^k	30.54^k	30.54^k	18.3^k	35.9^k
	Guaranteed Ultimate Tensile Strength (Stress at Guaranteed Minimum Ultimate Load)	27.12^k (120,000 psi)	72.70^k (120,000 psi)	72.70^k (120,000 psi)	58.14^k (60,000 psi)	114.0^k (60,000 psi)
	Guaranteed Yield Strength (Minimum Guaranteed Yield Stress)	20.79^k (92,000 psi)	55.75^k (92,000 psi)	55.75^k (92,000 psi)	34.9^k (36,000 psi)	68.4^k (36,000 psi)
	Guaranteed Proof Load (Minimum Guaranteed Proof Load Stress)	19.21^k (85,000 psi)	51.5^k (85,000 psi)	51.5^k (85,000 psi)		
UPPER CYCLIC LOAD LEVELS	100% Guaranteed Yield Strength, kips	20.79	55.75	55.75	34.9	68.4
	67% Guaranteed Yield Strength, kips	13.9	37.35	37.35	23.38	45.8
	33% Guaranteed Yield Strength, kips	6.86	18.4	18.4	11.5	22.57
	10% Guaranteed Yield Strength, kips	2.08	5.57	5.57	3.49	6.84
LOWER CYCLIC LOAD LEVEL	% of Upper Cyclic Load Level	0	0	0	0	0
PRELOADS (ELONGATION, INCHES) — ANCHOR BARS	100% Guaranteed Yield Strength, kips	-	-	55.8 (.0364 for 16" length) (.0605 for 24" length)	34.9 (.0213 for 19" length) (.0442 for 46" length)	68.4 (.0265 for 27" length)
	55% Guaranteed Yield Strength, kips	-	-	30.7 (.0208 for 16" length) (.0333 for 24" length)	19.2 (.0112 for 19" length) (.0241 for 46" length)	37.6 (.0140 for 27" length)
PRELOADS (ELONGATION, INCHES) — CAP SCREWS	1/3 Turn Past Snug Tight	20.8 (>0.0013)	55.75 (>0.004)			
	Snug Tight (80 ft. lbs.)	12 (0.0080)	7 (0.0004)			

Note: Elongations shown are from load vs. elongation curves displayed in Appendix D.

4.4.1.4 Length Measurements

During the testing, length readings were taken periodically to determine if there was a loss of preload and to indicate (by elongation) impending failure (see Figure 7).

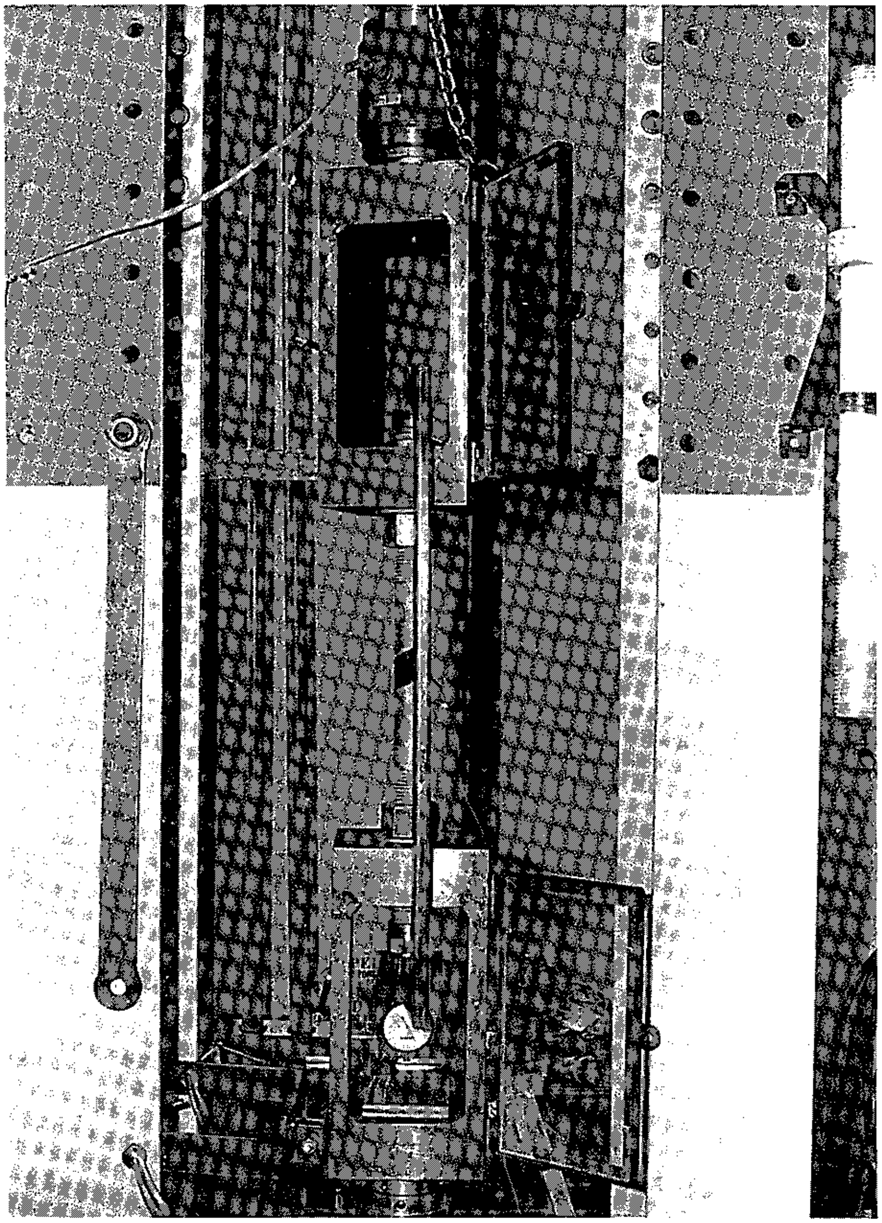


Figure 7. Length measurement of anchor bar being tested.

Thermocouples were attached to the specimens and to a reference anchor bar so that accurate temperatures of both could be monitored. When necessary, the length readings of the specimens were corrected due to differences and changes in bar temperatures.

4.4.1.5 Duration of Testing

A minimum of three specimens were tested at each preload level and stress range if they failed before reaching two million cycles. If a specimen reached two million cycles without failing, its life was considered infinite and only one or two specimens were tested.

4.4.2 Cap Screws

4.4.2.1 Mounting Setup

The test fixtures for applying cyclic loads to the cap screws were designed so that two cap screws at diagonal corners of a square mast arm plate were tested simultaneously. Cyclic tensile forces combined with realistic prying loads as would occur in an actual structure under wind loading were applied to the cap screws at the same time.

Top and bottom views of typical assembled cap screw fixtures are shown in Figures 8 and 9. To transmit the applied external load to the 5/8-inch-diameter cap screws, a 1 1/4-inch-diameter bolt was inserted through the center of the simulated mast arm connection plate. Two thick hardened washers were positioned on both sides of the mast arm plate and sandwiched by this 1 1/4-inch-diameter bolt as shown in Figure 10. So that the prying action on these test specimens would be similar to that on actual mast arm

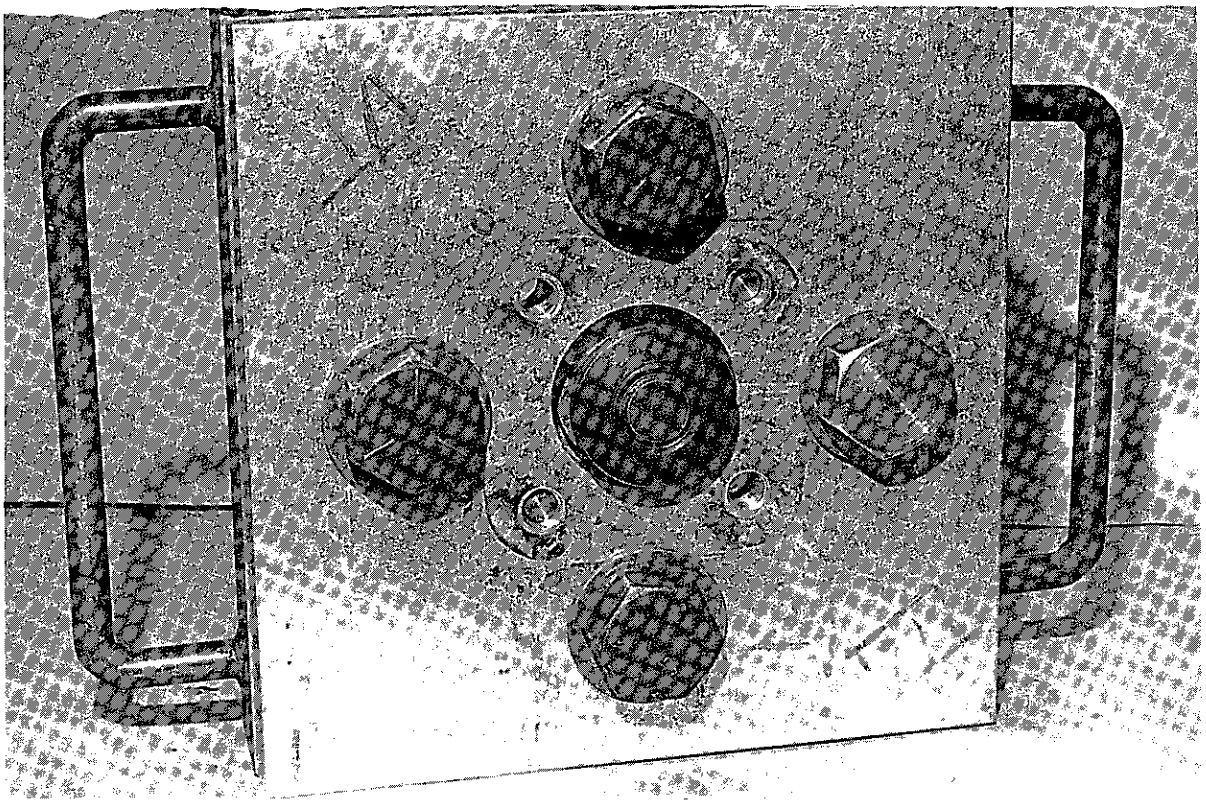
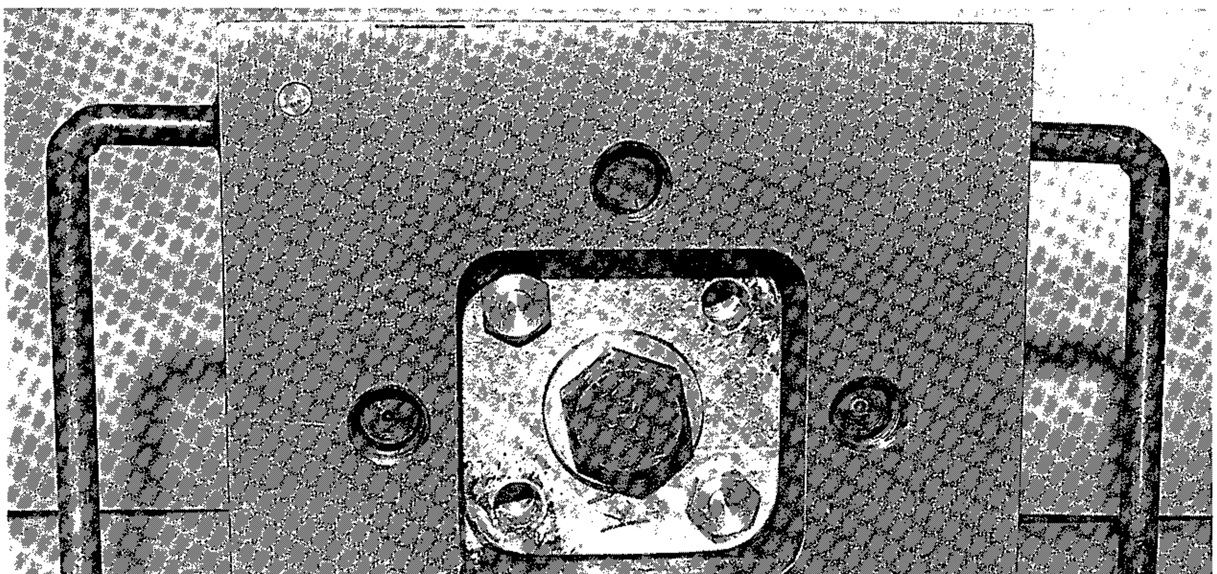


Figure 8. Top view of fixture for testing 5/8-inch-diameter cap screws.



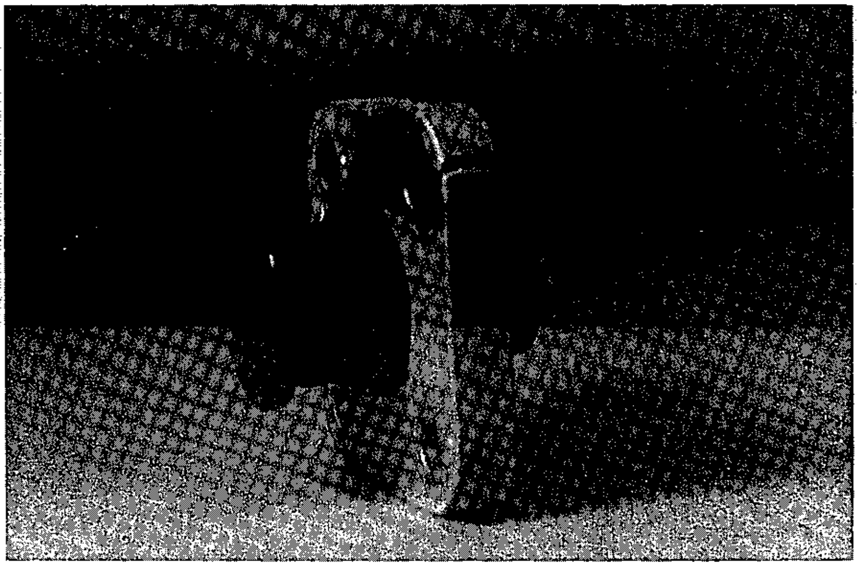


Figure 10. Loading bolt with two hardened washers, mast arm plate, and domed nut.

connections, the dimension from the center of the cap screws to the edge of these washers was the same as the distance on actual mast arm plates from the center of the cap screws to the toe of the fillet weld attaching the mast arm tube. A special domed nut, through which the external load was applied to the mast arm plate, was screwed onto the one end of the 1 1/4-inch-diameter center bolt and tightened. The curved surface of the nut matched a concave loading head on the upper crosshead of the testing machine, as shown in Figure 11.

The use of a curved washer made centering the specimen in the testing machine much easier. A similar fixture was used to test the 1-inch-diameter cap screws (see Figure 12). The mast arm plate was fastened to the simulated pole plate with the two cap screws that were placed diagonally opposite each other. The pole plate was then securely attached to the loading fixture plate with four 1 1/4-inch-diameter high-strength bolts (Figures 3 and 10).

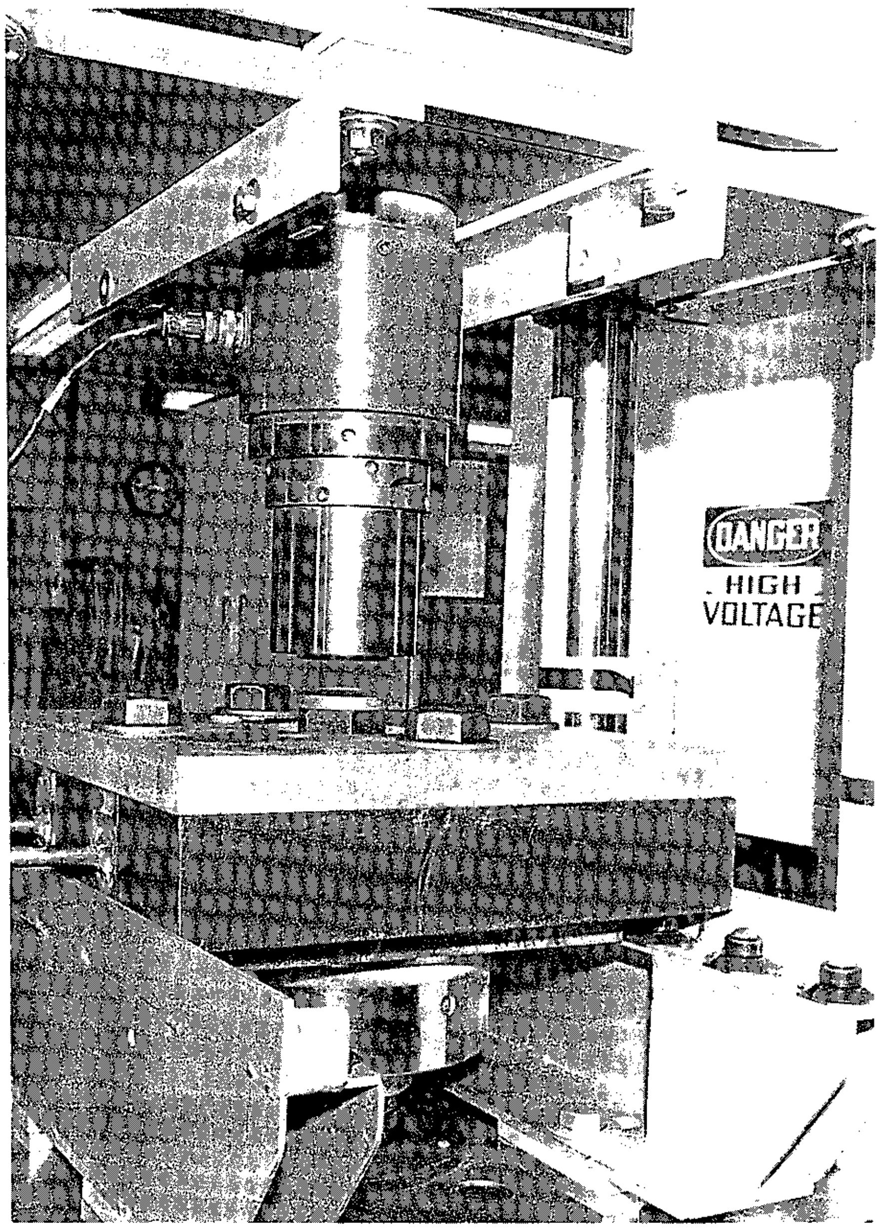


Figure 11. Typical setup for testing 5/8-inch-diameter cap screws.

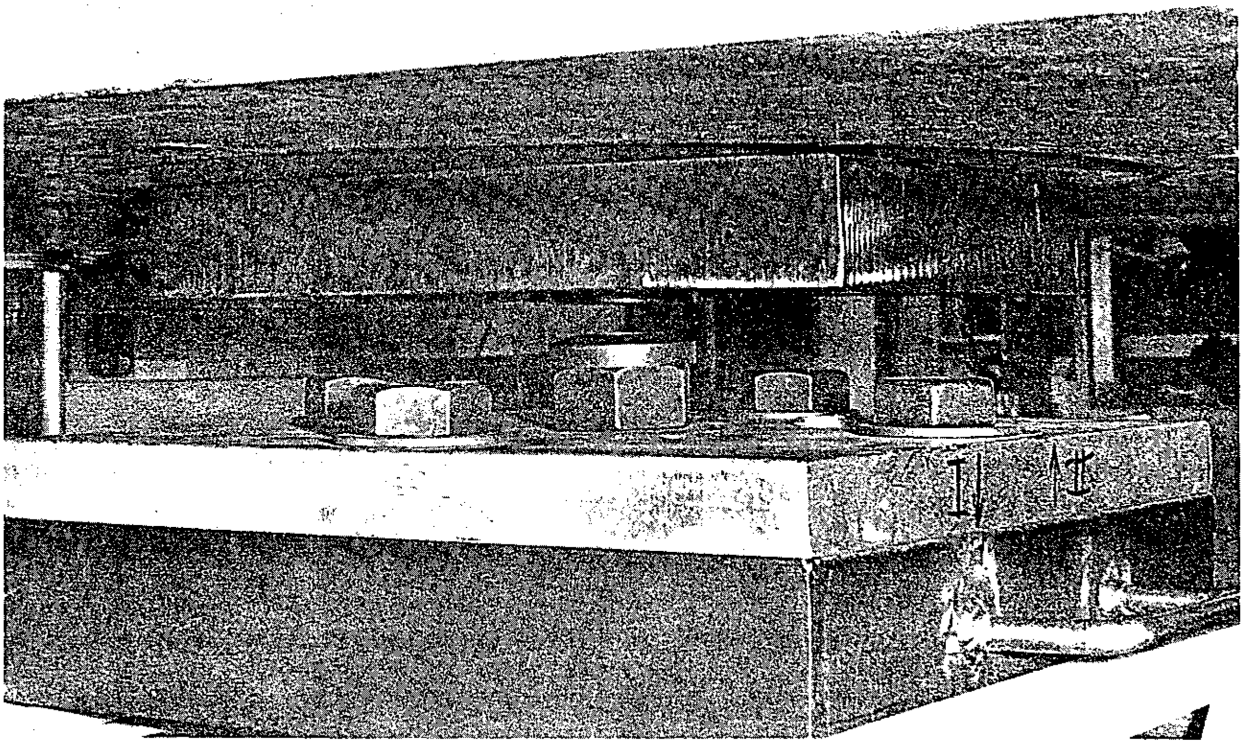


Figure 12. Test setup for 1-inch-diameter cap screws.

Prior to testing all cap screws, they were lubricated by dipping them in a solution of Johnson's Wax-Plate 15 and water (1:5). This lubrication helped to prevent galling and provided a more uniform preload in the cap screws.

4.4.2.2 Preloads and Stress Ranges

Two preloads and four external loads were used to test the cap screws. The preloads used were snug tight (80 ft-lbs) and 1/3 of a turn past snug tight. The external stress ranges used were 0-94.17%, 0-67%, 0-33% and 0-10% of guaranteed minimum yield stress (Table 11). These stress ranges were increased by 500 pounds at both the upper and lower load levels because of limitations imposed by the testing machines. The upper external load level of 94.17% of guaranteed yield was used rather than 100% of guaranteed yield shown in Table 11 to insure that the large load would not damage the small MTS testing machine having a 50-kip dynamic load capacity.

4.4.2.3 Length Measurements

During the testing, cap screw lengths were measured periodically to determine if there was a loss of preload and to indicate impending failure (see Figure 13).

4.4.2.4 Duration of Testing

A minimum of four specimens were tested at each preload and external load if they failed before reaching two million cycles. If a specimen reached two million cycles without failing, only one or two specimens were tested.

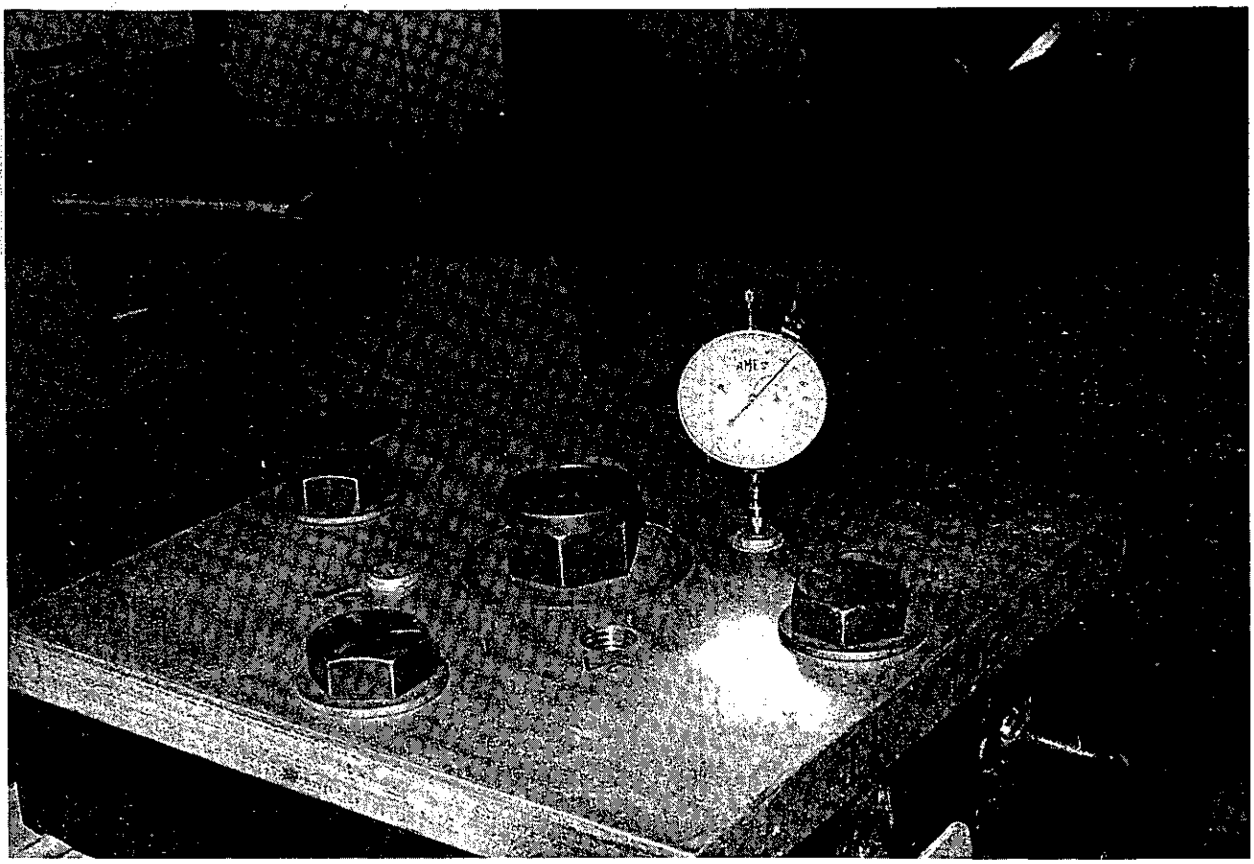


Figure 13. Length measurement of a cap screw being tested.

5. DISCUSSION OF TEST RESULTS

5.1 General Discussion

In the cyclic testing of the anchor bars performed in this research project, the following variables were analyzed to determine how they affected fatigue life: grip length, bar diameter, steel type and the preload condition. In the cyclic load tests conducted on high-strength cap screws, diameter and preload condition were considered important variables when determining the fatigue life of the cap screws used in typical lighting standard mast arm-to-pole connections. The results of all the cyclic tests are summarized in Tables A1 through A7 in Appendix A.

The stress range based on the externally applied load for each specimen was plotted versus the number of cycles to failure to develop the S-N diagrams shown in Appendices B (anchor bars) and C (cap screws). This stress range (external load divided by stress area) was chosen to plot the S-N curves to make a comparison of the different preload conditions more convenient.

Currently the nuts on anchor bars used by Caltrans to anchor structural supports for signs and luminaires are installed in the snug tight preload condition. In this condition the anchor bars are bonded to the concrete foundation in which they are placed. This bond length required to develop the strength of an anchor bar has been found to be approximately ten bar diameters and, thus, is simulated in these tests by the short bar lengths. The longer anchor bars tested in this research represent anchorages which have purposely been debonded over their entire bar length, enabling the full length to be preloaded by tightening a single nut. This system is currently not used by Caltrans.

In order to objectively evaluate the fatigue lives of anchor bars under different conditions, one must compare test results of the short double nutted bars whose outer nuts were tightened snug tight and 1/3 of a turn past snug tight with those of the long, fully preloaded, single nutted bars. In the case of the 1 3/4-inch-diameter A307 anchor bars, however, such comparisons of fatigue lives are not possible as only the short 27-inch-long bars were tested.

5.2 Anchor Bars

5.2.1 Effect of Preload Condition on Fatigue Life

5.2.1.1 Comparison of Fatigue Results of Anchor Bars with Double Nuts Tightened to the Snug Tight Condition with Those of Similar Bars Tightened 1/3 Turn Past Snug Tight

The effects of tightening the top (outside) nut of the double nutted anchor bars from snug tight to 1/3 of a turn past snug tight on fatigue life is shown in Figures B1 through B5 and Figure B22 in Appendix B. All of the anchor bars exhibited a longer fatigue life when tightened to 1/3 of a turn past snug tight with the 1 3/4-inch-diameter x 27-inch anchor bars showing the largest increase in fatigue life, almost ten-fold (Figure B5). The 1 1/4-inch-diameter x 19-inch and 1 1/4-inch-diameter x 46-inch anchor bars show an increase in fatigue life of about three times (Figures B3 and B4) and the fatigue life will double for both the 1-inch-diameter x 24-inch and 1-inch-diameter x 16-inch anchor bars (Figures B1 and B2). Overall the fatigue life of the anchor bars tested was at least doubled by tightening the upper nut to 1/3 of a turn past snug tight.

5.2.1.2 Comparison of Fatigue Results of Anchor Bars with Double Nuts Tightened Snug Tight Condition with Those of Preloaded Single Nutted Anchor Bars

As can be seen from the S-N curves shown in Figures B1 through B5 of Appendix B, a substantial increase in anchor bar fatigue life can be achieved by preloading an unbonded anchor bar with single nuts on each end over the entire bar length as opposed to a fully bonded double nutted anchor bar with the top nuts tightened to snug tight. The 1-inch--diameter A449 bars would benefit the most from this type of installation. By using single nuts on a 1-inch-diameter x 24-inch anchor bar and preloading to 55% of Fy the fatigue life is increased 50 times over the 1-inch-diameter x 16-inch anchor bars with double nuts tightened to the snug tight condition as shown in Figures B1 and B2. The single nutted 1 1/4-inch-diameter x 46-inch bars at a preload of 55% of Fy will have a fatigue life 4 times greater than the double nutted 1 1/4-inch-diameter x 19-inch bars whose top nuts are tightened to a snug tight condition (see Figures B3 and B4 of Appendix B for comparison). The single nutted 1 3/4-inch-diameter x 27-inch anchor bars tightened to a preload of 55% of Fy will have a fatigue life 7 times greater than the double nutted 1 3/4-inch-diameter x 27-inch bars tightened only to snug tight (Figure B5). Comparisons are made only with the preloaded bar at 55% of Fy because the A307 anchor bars did not fail at the 100% of Fy preload condition and the S-N curve could not be developed. Overall there is at least a four-fold increase in fatigue life if one preloads the entire bar to 55% of Fy as opposed to the current practice of tightening the top nut of a double nutted bar to a snug tight condition.

5.2.1.3 Comparison of Fatigue Results of Anchor Bars with Double Nuts Tightened 1/3 Turn Past Snug Tight with Those of Preloaded Single Nutted Anchor Bars

A comparison of the single nutted anchor bars preloaded to 55% of Fy with the double nutted anchor bars with the top nuts tightened 1/3 of a turn past snug tight is shown in Figure B23. The single nutted 1-inch-diameter x 24-inch A449 anchor bars preloaded at 55% of Fy show a fatigue life 30 times that of double nutted anchor bars with top nuts tightened to 1/3 of a turn past snug tight. The single nutted 1 1/4-inch-diameter x 46-inch A307 anchor bars tightened to 55% of Fy show only a very slight increase in fatigue life, about 1.5 times that of a double nutted anchor bar with outer nuts tightened 1/3 of a turn past snug tight. The test results from the 1 3/4-inch-diameter A307 anchor bars differ from those of other bars. The 1 3/4- inch-diameter double nutted bars tightened to 1/3 of a turn past snug tight have a fatigue life of approximately 2 times that of the 1 3/4-inch-diameter single nutted bars tightened to 55% of Fy. From comparisons of fatigue results of the 1 1/4-inch-diameter anchor bars with those of the 1 3/4-inch-diameter anchor bars, an apparent inconsistency can be noted. It is, however, small and can probably be explained by the small number of specimens tested and the relatively large scatter in the resulting data. It is interesting to note that the 1 1/4-inch-diameter and 1 3/4-inch-diameter A307 bars have close to the same fatigue life for these two preload conditions while a similar comparison with fatigue results of the 1-inch-diameter A449 bars indicates a much greater fatigue life of single nutted bars preloaded to 55% of Fy as compared to the doubled nutted anchor bars tightened to 1/3 of a turn past snug tight.

5.2.2 Effect of Steel Type on Fatigue Life

The apparent effect of steel types tested on fatigue life varies considerably, depending on whether anchor bars were double or single nutted and in what stress range the bars were cycled. In general, the 1-inch-diameter A449 anchor bars with single nuts and preloaded at 55% of their minimum yield point, as shown in Figures B17 and B20, have endurance limits above the guaranteed yield stresses of the similarily preloaded mild steel anchor bars. The fatigue life of the 1 1/4-inch-diameter and 1 3/4-inch-diameter mild steel anchor bars preloaded with single nuts to 100% of their guaranteed yield point exceeded two million cycles without failure as shown in Appendix A tables. The single nutted high-strength bars preloaded to 55.8 kips (100% of their minimum guaranteed yield point) also had fatigue lives which exceeded two million cycles at a stress range of approximately 61.6 ksi.

The fatigue lives of both high-strength and mild steel double nutted anchor bars with the outer nuts tightened 1/3 turn past snug tight were less than similar preloaded bars having single nuts.

For specimens having double nuts, the high-strength bars, however, had noticeably shorter fatigue lives than those of the mild steel bars when subjected to maximum stress levels below approximately 36 ksi, as shown in Figures B15, B16, B18, B19, and B21. Restating this important point another way, all mild steel bars tested with double nuts exhibited superior fatigue lives compared with similar high-strength anchor bars for all stress ranges equal to or less than 36 ksi.

5.2.3 Significance of Fracture Locations

Anchor bar fractures were classified into four different break locations shown in Figure 18.

Typically anchor bars having single nuts on each end of the bar and tested with preloads of 55% and 100% of their guaranteed yield strength fractured just above the base of the nut, at location 1. Failure at this location was expected because of high stress concentrations that occur at the root of the bar threads at this point.

All of the anchor bars having two nuts on each bar end (double nutted) and tested with the outer nut tightened to a snug tight condition also failed at location 1. This is because the very small preload (Figure D5, D6, and D7) imparted to the short section of bar between the leveling and outer nuts was quickly lost due to the uneven galvanized surface being flattened as the bars were cycled. With no tension between the two nuts, the bars behaved as though they were single nutted without any preload and therefore failed at location 1 in the same manner as the other single nutted anchor bars.

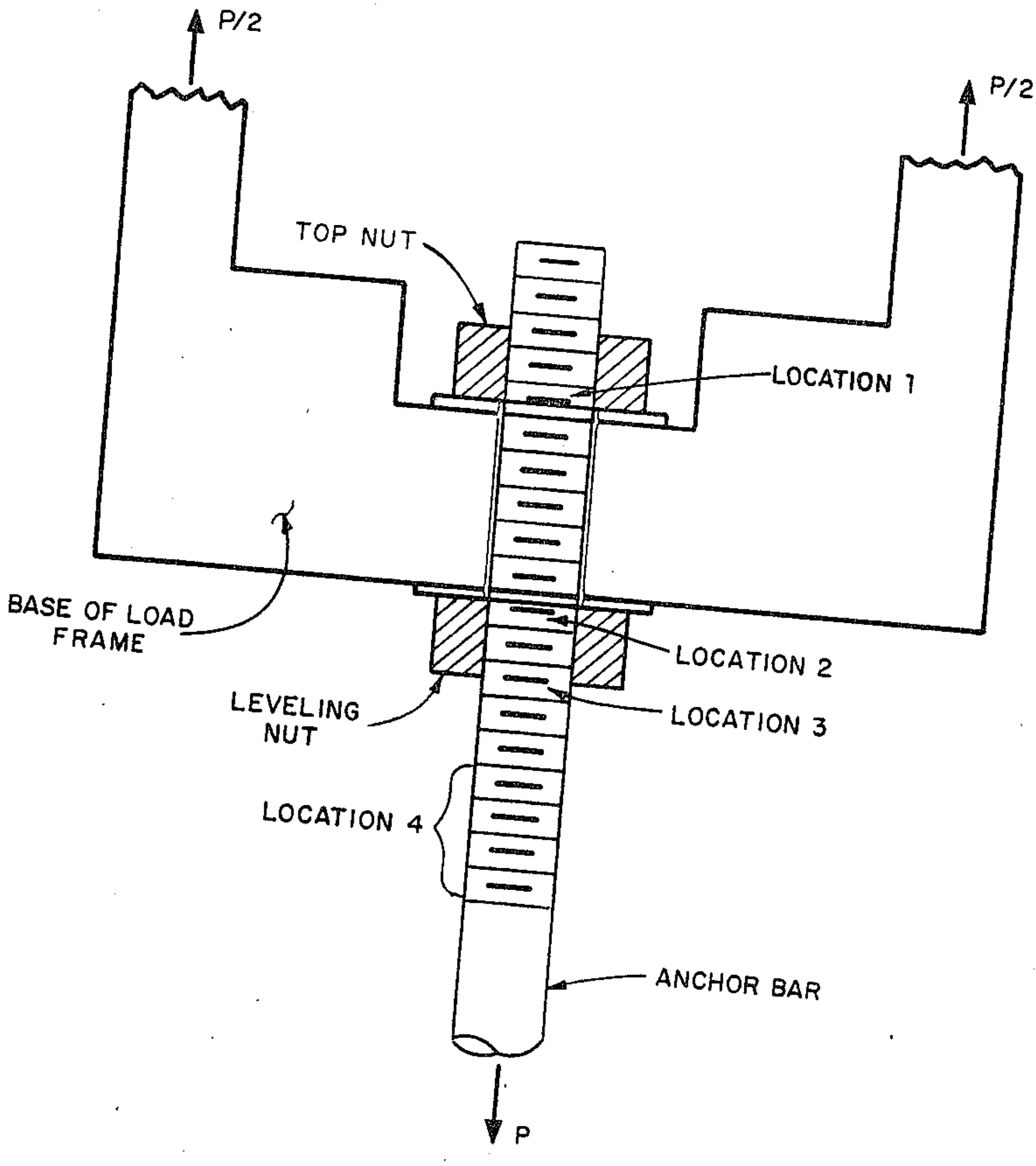


Figure 18. Fatigue break location diagram for anchor bar cyclic tests.

The double nutted anchor bars whose outer nuts were tightened 1/3 of a turn past snug tight failed in several different locations as shown in Tables 12, 13, and 14.

These bars had large initial preload within the short grip length between the leveling and locking nuts when tightened to 1/3 of a turn past snug tight as shown in Figures D5 through D7. Consequently as the bars were cycled, the middle section of the bar that had no preload was subjected to the full external load and thus experienced the largest stress change. Therefore, the expected failure zone would lie in this area of the bar. All but one of the 1 1/4-inch-diameter ASTM A307 bars failed in the center, threaded portion of the bar at locations 3 or 4, (see Table 13) and a majority of the 1-inch-diameter ASTM A449 bars also failed in this region (see Table 12). The remaining 1-inch-diameter ASTM A449 bars and most of the 1 3/4-inch-diameter ASTM A307 bars (see Table 14) failed between the leveling and outer nuts at locations 1 or 2, because for some reason they evidently lost most of their initial preload.

5.2.4 Effect of Length on Fatigue Life

The fatigue test results shown in Figures B6 through B11 of Appendix B for the 1-inch-diameter A449 anchor bars and the 1 1/4-inch-diameter A307 anchor bars indicate that differences in the bar lengths as tested had no significant effect on fatigue life.

Comparisons of fatigue data of the 1-inch-diameter x 16-inch anchor bars with that from 1-inch-diameter x 24-inch anchor bars for all of the test conditions (Figure B6, B7, and B8), and data from the 1 1/4-inch-diameter x 19-inch bars

Table 12. Break locations for 1-inch-diameter double nutted anchor bars with the 1/3 turn past snug tight preload condition.

12a: 1-inch-diameter x 16-inch anchor bars, snug tight + 1/3 turn.

BREAK LOCATION	SPECIMEN NO.	LOAD RANGE, kips	CYCLES TO FAILURE
(1)	2A	0.5-56.3	4,540
(1)	3A	0.5-56.3	6,930
(3)	7A	0.5-18.9	97,410
(3)	5A	0.5-37.8	22,760
(4)	8A	0.5-18.9	117,370
(4)	9A	0.5-18.9	129,470
(4)	1A	0.5-56.3	6,910
(4)	4A	0.5-37.8	18,880
(4)	6A	0.5-37.8	22,120
None	10A	0.5-6.1	None

12b: 1-inch-diameter x 24-inch anchor bars, snug tight + 1/3 turn.

BREAK LOCATION	SPECIMEN NO.	LOAD RANGE, kips	CYCLES TO FAILURE
(1)	1LA	0.5-56.3	6,429
(1)	1LA-V	0.5-56.3	3,180
(1)	2LA	0.5-56.3	4,742
(2)	5LA	0.5-37.8	16,238
(2)	7LA	0.5-18.9	137,758
(3)	9LA	0.5-18.9	111,240
(4)	4LA	0.5-37.8	22,071
(4)	8LA	0.5-18.9	84,786
(4)	6LA	0.5-37.8	17,660
(4)	3LA	0.5-56.3	7,109
None	10LA	0.5-6.1	None

Table 13. Break locations for 1 1/4-inch-diameter double nutted anchor bars with the 1/3 turn past snug tight preload condition.

13a: 1 1/4-inch-diameter x 19-inch anchor bars, snug tight + 1/3 turn.

BREAK LOCATION	SPECIMEN NO.	LOAD RANGE, kips	CYCLES TO FAILURE
(2)	1.25-19-14	0.5-35.4	214,190
(4)	1.25-19-15	0.5-35.4	206,070
(4)	1.25-19-13	0.5-35.4	120,700
(4)	1.25-19-13X	0.5-35.4	120,650
(4)	1.25-19-25	0.5-29.5	484,950
(4)	1.25-19-26	0.5-29.5	480,720
(4)	1.25-19-27	0.5-29.5	565,550
None	1.25-19-16	0.5-23.9	None
None	1.25-19-17	0.5-23.9	None
None	1.25-19-19	0.5-12.0	None

13b: 1 1/4-inch-diameter x 46-inch anchor bars, snug tight + 1/3 turn.

BREAK LOCATION	SPECIMEN NO.	LOAD RANGE, kips	CYCLES TO FAILURE
(3)	1.25-46-10	0.5-35.4	90,560
(3)	1.25-46-11	0.5-35.4	84,400
(3)	1.25-46-13	0.5-29.5	117,210
(4)	1.25-46-12	0.5-35.4	111,830
(4)	1.25-46-15	0.5-29.5	196,340
(4)	1.25-46-14	0.5-29.5	185,820
(4)	1.25-46-13X	0.5-29.5	275,510
None	1.25-46-16	0.5-23.9	None

Table 14. Break locations for 1 3/4-inch-diameter double nutted anchor bars with the 1/3 turn past snug tight preload condition.

1 3/4-inch-diameter x 27-inch anchor bars, snug tight + 1/3 turn.

BREAK LOCATION	SPECIMEN NO.	LOAD RANGE, kips	CYCLES TO FAILURE
(2)	1.75-27-9	0.5-68.9	76,360
(2)	1.75-27-11	0.5-68.9	160,460
(2)	1.75-27-12	0.5-68.9	68,930
(2)	1.75-27-31	0.5-57.5	1,197,250
(2)	1.75-27-32	0.5-57.5	1,279.930
(3)	1.75-27-32	0.5-57.5	595,200
(4)	1.75-27-10	0.5-68.9	177,200
None	1.75-27-13	0.5-46.3	None
None	1.75-27-14	0.5-46.3	None

with that of 1 1/4-inch-diameter x 46-inch bars preloaded to 55% of Fy (Figure B11), show that fatigue lives are nearly identical. However, from a similar comparison between test results of the 1 1/4-inch-diameter x 19-inch bars with those of 1 1/4-inch-diameter x 46-inch anchor bars at the snug tight and 1/3 turn past snug tight conditions shown in Figures B9 and B10, a conclusion somewhat contrary to that previously made can be drawn. This apparent difference can be explained by the small number of data points and the relative closeness of the groups of data which can significantly affect the determination of the slopes of the S-N curves.

5.2.5 Effect of Diameter on Fatigue Life

In general, the effect of variations in bar diameter on fatigue life appears to be small, if not negligible. Apparent differences in fatigue life that did occur can be attributed to the small number of specimens tested and the large spread in data typically found in fatigue testing.

A comparison of the S-N curves for the 1 1/4-inch-diameter x 19-inch and 1 3/4-inch-diameter x 27-inch anchor bars (Figure B12, B13, and B14) shows that for single nutted bars preloaded to 55% of Fy and double nutted bars tightened 1/3 turn past snug tight, the 1 1/4-inch-diamter and 1 3/4-inch-diameter bars have similar fatigue lives while at the snug condition the fatigue life of the double nutted 1 1/4-inch-diameter anchor bar appears to be somewhat better than that of the 1 3/4-inch-diameter bars tested.

5.3 Cap Screws

5.3.1 Effect of Cap Screw Preload on Fatigue Life

In both the 5/8-inch-diameter and 1-inch-diameter cap screws tested, tightening them an additional 1/3 of a turn past snug tight prestressed the cap screws past their yield point (Figure D1 and D3). This higher prestress level dramatically increased the fatigue life of both diameters of cap screws over similar cap screws brought only to a snug tight condition. The increase in fatigue life due to the larger preload was from 4 to 40 times for the 5/8-inch-diameter cap screws and from 2.5 to 80 times for the 1-inch- diameter cap screws depending on the external stress range as shown in Figures C1 and C2.

5.3.2 Effect of Cap Screw Diameter on Fatigue Life

The fatigue lives of A325 cap screws, when preloaded to the same internal stress level, is independent of cap screw diameter.

When the cap screws tested were tightened 1/3 of a turn past the snug tight condition, the fatigue lives of both the 5/8-inch- diameter and 1-inch-diameter cap screws were essentially the same (Figure C4). At this preload condition both cap screws had been stretched past their yield point. They both had nearly the same internal stress and hence the same fatigue life. The slightly longer fatigue life that the 5/8-inch-diameter cap screws exhibited is probably due to the small differences in their actual preload stresses and also the choice of scales used to plot their S-N curves resulting in lines with very flat slopes.

As shown in Figure C3, the 5/8-inch-diameter cap screws exhibited a fatigue life which is approximately 10 times longer than the 1-inch-diameter cap screws when tightened to the snug tight condition. This can be explained by examining the load versus elongation curves for these cap screws shown in Figures D1 and D3. The 5/8-inch-diameter cap screws had a 12 kip preload when tightened to the snug tight condition (80 ft-lbs); this preload resulted in a 44.2 ksi stress in the small cap screws. The 1-inch-diameter cap screws had a 10 kip preload at the snug tight condition which resulted in a stress of only 16.5 ksi. Thus, it was the higher internal stress present in the 5/8-inch-diameter cap screws tightened to the snug tight condition that gave them a longer fatigue life.

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TABLE A1

Summary of Fatigue Tests of 1"ϕ x 16" A449 Anchor Bars

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Anchor Bar Preload (kips)	Total No. of Cycles Tested	Failure* Location
1	92.0	+0.2 to +56.0	0[1]	6,900	1
2	92.0	+0.2 to +56.0	0[1]	4,220	1
3X	92.0	+1.0 to +56.8	0[1]	4,338	1
3	90.8	+1.0 to +56.0	0[1]	4,390	1
6	61.7	+1.0 to +38.4	0[1]	14,329	1
4	60.7	+1.0 to +37.8	0[1]	9,600	1
5	60.7	+1.0 to +37.8	0[1]	10,705	1
7	30.4	+1.0 to +19.4	0[1]	84,900	1
8	30.4	+1.0 to +19.4	0[1]	77,563	1
9	29.7	+1.0 to +19.0	0[1]	66,044	1
10	9.2	+0.5 to + 6.1	0[1]	3,134,607	No Failure
11	9.2	+0.5 to + 6.1	0[1]	3,704,900	No Failure
1A	92.0	+0.5 to +56.3	0[2]	6,910	4
2A	92.0	+0.5 to +56.3	0[2]	4,540	1
3A	92.0	+0.5 to +56.3	0[2]	6,930	1
4A	61.6	+0.5 to +37.8	0[2]	18,880	4
5A	61.6	+0.5 to +37.8	0[2]	22,760	3
6A	61.6	+0.5 to +37.8	0[2]	22,120	4
7A	30.4	+0.5 to +18.9	0[2]	97,410	3
8A	30.4	+0.5 to +18.9	0[2]	117,370	4
9A	30.4	+0.5 to +18.9	0[2]	129,470	4
10A	9.2	+0.5 to + 6.1	0[2]	2,123,000	No Failure
13A	92.0	+0.5 to +56.3	30.7[3]	10,940	1
14A	92.0	+0.5 to +56.3	30.7[3]	9,069	1
15A	92.0	+0.5 to +56.3	30.7[3]	6,590	1
14	91.6	+0.5 to +56.0	30.7[3]	8,250	1
15	91.6	+0.5 to +56.0	30.7[3]	13,620	1
13	91.1	+0.5 to +55.7	30.7[3]	11,320	1

TABLE A1 (Continued)

Summary of Fatigue Tests of 1"ϕ x 16" A449 Anchor Bars

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Anchor Bar Preload (kips)	Total No. of Cycles Tested	Failure* Location
16A	61.6	+0.5 to +37.8	30.7[3]	148,000	1
17A	61.6	+0.5 to +37.8	30.7[3]	87,550	1
18A	61.6	+0.5 to +37.8	30.7[3]	118,300	1
16	61.6	+0.3 to +37.6	30.7[3]	64,590	1
17	61.6	+0.3 to +37.6	30.7[3]	123,840	1
18	61.6	+0.3 to +37.6	30.7[3]	93,360	1
1.0-16-2	55.0	+0.5 to +33.8	30.7[3]	276,700	1
1.0-16-3	55.0	+0.5 to +33.8	30.7[3]	526,500	1
1.0-16-4	55.0	+0.5 to +33.8	30.7[3]	848,860	1
1.0-16-1	46.2	+0.5 to +28.5	30.7[3]	2,760,000	No Failure
19	30.4	+0.2 to +18.6	30.7[3]	2,044,830	No Failure
20	30.4	+0.3 to +18.7	30.7[3]	2,211,500	No Failure
20A	30.4	+0.5 to +18.9	30.7[3]	2,451,000	No Failure
21	92.0	+0.2 to +56.0	55.8[3]	92,430	1
22	92.0	+0.2 to +56.0	55.8[3]	127,950	1
25	92.0	+0.2 to +56.0	55.8[3]	67,570	1
23A	92.0	+0.5 to +56.3	55.8[3]	78,690	1
24A	92.0	+0.5 to +56.3	55.8[3]	96,460	1
22A	91.3	+0.5 to +55.8	55.8[3]	135,660	1
1.0-16-5	88.3	+0.5 to +54.0	55.8[3]	184,800	1
1.0-16-9	83.3	+0.5 to +51.0	55.8[3]	826,000	1
1.0-16-10	83.3	+0.5 to +51.0	55.8[3]	370,100	1
1.0-16-11	83.3	+0.5 to +51.0	55.8[3]	490,100	1
1.0-16-6	80.0	+0.5 to +49.0	55.8[3]	41,900	1
1.0-16-8	76.7	+0.5 to +47.0	55.8[3]	2,009,200	No Failure
23	61.6	+0.2 to +37.6	55.8[3]	2,037,980	No Failure
24	61.6	+0.2 to +37.6	55.8[3]	2,370,900	No Failure
25A	61.6	+0.5 to +37.8	55.8[3]	3,365,000	No Failure

*See Section 5.2.3 and Figure 18 for explanation of failure location.

[1] Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened until snug tight (100 ft-lbs).

[2] Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened 1/3 of a turn past snug tight (100 ft-lbs).

[3] A single nut was used on each bar end. Steel spacer sleeves were positioned between the upper and lower load frames so that the full length of bar between end nuts could be preloaded.

TABLE A2

Summary of Fatigue Tests of 1"ϕ x 24" A449 Anchor Bars

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Anchor Bar Preload (kips)	Total No. of Cycles Tested	Failure* Location
2L	92.0	+1.0 to +56.8	0[1]	3,101	1
3L	92.0	+1.0 to +56.8	0[1]	3,136	1
1L	90.4	+1.0 to +55.8	0[1]	3,729	1
5L	61.7	+1.0 to +38.4	0[1]	10,494	1
6L	61.7	+1.0 to +38.4	0[1]	11,260	1
4L	60.7	+1.0 to +37.8	0[1]	15,350	1
7L	29.7	+1.0 to +19.0	0[1]	54,862	1
8L	29.7	+1.0 to +19.0	0[1]	62,800	1
9L	29.7	+1.0 to +19.0	0[1]	53,267	1
10L	9.2	+0.5 to + 6.1	0[1]	5,462,630	No Failure
12L	9.2	+0.5 to + 6.1	0[1]	3,200,000	No Failure
1LA-V	92.0	+0.5 to +56.3	0[2]	3,180	1
1LA	92.0	+0.5 to +56.3	0[2]	6,429	1
2LA	92.0	+0.5 to +56.3	0[2]	4,742	1
3LA	92.0	+0.5 to +56.3	0[2]	7,109	4
4LA	61.6	+0.5 to +37.8	0[2]	22,071	4
5LA	61.6	+0.5 to +37.8	0[2]	16,238	2
6LA	61.6	+0.5 to +37.8	0[2]	17,660	4
7LA	30.4	+0.5 to +18.9	0[2]	137,758	2
8LA	30.4	+0.5 to +18.9	0[2]	84,786	4
9LA	30.4	+0.5 to +18.9	0[2]	111,240	3
10LA	9.2	+0.5 to + 6.1	0[2]	2,203,000	No Failure
13L	92.0	+0.5 to +56.3	30.7[3]	9,531	1
14L	92.0	+0.5 to +56.3	30.7[3]	7,714	1
15L	92.0	+0.5 to +56.3	30.7[3]	7,803	1
16L	61.6	+0.5 to +37.8	30.7[3]	134,804	1
17L	61.6	+0.5 to +37.8	30.7[3]	204,500	1
18L	61.6	+0.5 to +37.8	30.7[3]	219,052	1

TABLE A2 (Continued)

Summary of Fatigue Tests of 1" x 24" A449 Anchor Bars

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Anchor Bar Preload (kips)	Total No. of Cycles Tested	Failure* Location
1.0-24-5	55.0	+0.5 to +33.8	30.7 [3]	2,559,000	No Failure
1.0-24-6	55.0	+0.5 to +33.8	30.7 [3]	3,540,000	No Failure
1.0-24-4	51.0	+0.5 to +31.4	30.7 [3]	2,550,000	No Failure
19L	30.4	+0.5 to +18.9	30.7 [3]	2,000,000	No Failure
20L	30.4	+0.5 to +18.9	30.7 [3]	2,030,000	No Failure
21L	92.0	+0.5 to +56.3	55.8 [3]	478,687	1
22L	92.0	+0.5 to +56.3	55.8 [3]	1,675,640	1
25L	92.0	+0.5 to +56.3	55.8 [3]	432,880	1
1.0-24-2	92.0	+0.5 to +56.3	55.8 [3]	997,700	1
23L	61.6	+0.5 to +37.8	55.8 [3]	2,010,000	No Failure
24L	61.6	+0.5 to +37.8	55.8 [3]	3,380,000	No Failure

*See Section 5.2.3 and Figure 18 for explanation of failure location.

[1] Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened until snug tight (100 ft-lbs).

[2] Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened 1/3 of a turn past snug tight (100 ft-lbs).

[3] A single nut was used on each bar end. Steel spacer sleeves were positioned between the upper and lower load frames so that the full length of bar between end nuts could be preloaded.

TABLE A3

Summary of Fatigue Tests of 1 1/4"ϕ x 19" A307 Anchor Bars

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Anchor Bar Preload (kips)	Total No. of Cycles Tested	Failure* Location
1.25-19-1	36.0	+0.5 to +35.4	0[1]	88,040	1
1.25-19-1X	36.0	+0.5 to +35.4	0[1]	63,630	1
1.25-19-2	36.0	+0.5 to +35.4	0[1]	49,410	1
1.25-19-3	36.0	+0.5 to +35.4	0[1]	46,870	1
1.25-19-4	24.1	+0.5 to +23.9	0[1]	499,160	1
1.25-19-4X	24.1	+0.5 to +23.9	0[1]	796,200	1
1.25-19-5	24.1	+0.5 to +23.9	0[1]	607,640	1
1.25-19-6	24.1	+0.5 to +23.9	0[1]	956,780	1
1.25-19-7	11.9	+0.5 to +12.0	0[1]	3,011,000	No Failure
1.25-19-13	36.0	+0.5 to +35.4	0[2]	120,700	4
1.25-19-13X	36.0	+0.5 to +35.4	0[2]	120,650	4
1.25-19-14	36.0	+0.5 to +35.4	0[2]	214,190	2
1.25-19-15	36.0	+0.5 to +35.4	0[2]	206,070	4
1.25-19-25	29.9	+0.5 to +29.5	0[2]	484,950	4
1.25-19-26	29.9	+0.5 to +29.5	0[2]	480,720	4
1.25-19-27	29.9	+0.5 to +29.5	0[2]	565,550	4
1.25-19-16	24.1	+0.5 to +23.9	0[2]	2,558,770	No Failure
1.25-19-17	24.1	+0.5 to +23.9	0[2]	2,485,000	No Failure
1.25-19-19	11.9	+0.5 to +12.0	0[2]	2,136,000	No Failure
1.25-19-28	36.0	+0.5 to +35.4	19.2[3]	55,940	1
1.25-19-28X	36.0	+0.5 to +35.4	19.2[3]	105,390	1
1.25-19-29	36.0	+0.5 to +35.4	19.2[3]	148,040	1
1.25-19-30	36.0	+0.5 to +35.4	19.2[3]	99,080	1
1.25-19-40	29.9	+0.5 to +29.5	19.2[3]	574,600	1
1.25-19-41	29.9	+0.5 to +29.5	19.2[3]	278,600	1
1.25-19-41X	29.9	+0.5 to +29.5	19.2[3]	609,260	1
1.25-19-42	29.9	+0.5 to +29.5	19.2[3]	599,930	1
1.25-19-31	24.1	+0.5 to +23.9	19.2[3]	2,113,000	No Failure
1.25-19-43	36.0	+0.5 to +35.4	34.9[3]	2,010,040	No Failure

TABLE A3 (Continued)

*See Section 5.2.3 and Figure 18 for explanation of failure location.

[1] Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened until snug tight (100 ft-lbs).

[2] Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened 1/3 of a turn past snug tight (100 ft-lbs).

[3] A single nut was used on each bar end. Steel spacer sleeves were positioned between the upper and lower load frames so that the full length of bar between end nuts could be preloaded.

TABLE A4

Summary of Fatigue Tests of 1 1/4"ϕ x 46" A307 Anchor Bars

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Anchor Bar Preload (kips)	Total No. of Cycles Tested	Failure* Location
1.25-46-1	36.0	+0.5 to +35.4	0[1]	37,640	1
1.25-46-2	36.0	+0.5 to +35.4	0[1]	29,170	1
1.25-46-3	36.0	+0.5 to +35.4	0[1]	36,900	1
1.25-46-4	24.1	+0.5 to +23.9	0[1]	71,260	1
1.25-46-4X	24.1	+0.5 to +23.9	0[1]	156,550	1
1.25-46-5	24.1	+0.5 to +23.9	0[1]	190,190	1
1.25-46-6	24.1	+0.5 to +23.9	0[1]	226,280	1
1.25-46-8	15.0	+0.5 to +15.0	0[1]	1,431,700	1
1.25-46-8A	15.0	+0.5 to +15.0	0[1]	999,800	1
1.25-46-9	15.0	+0.5 to +15.0	0[1]	1,046,900	1
1.25-46-9A	15.0	+0.5 to +15.0	0[1]	703,600	1
1.25-46-7	11.9	+0.5 to +12.0	0[1]	2,160,000	No Failure
1.25-46-10	36.0	+0.5 to +35.4	0[2]	90,560	3
1.25-46-11	36.0	+0.5 to +35.4	0[2]	84,400	3
1.25-46-12	36.0	+0.5 to +35.4	0[2]	111,830	4
1.25-46-13	29.9	+0.5 to +29.5	0[2]	117,210	3
1.25-46-13X	29.9	+0.5 to +29.5	0[2]	275,510	4
1.25-46-14	29.9	+0.5 to +29.5	0[2]	185,820	4
1.25-46-15	29.9	+0.5 to +29.5	0[2]	196,340	4
1.25-46-16	24.1	+0.5 to +23.9	0[2]	2,269,000	No Failure
1.25-46-19	36.0	+0.5 to +35.4	19.2[3]	129,310	1
1.25-46-20	36.0	+0.5 to +35.4	19.2[3]	164,190	1
1.25-46-21	36.0	+0.5 to +35.4	19.2[3]	137,800	1
1.25-46-22	29.9	+0.5 to +29.5	19.2[3]	552,240	1
1.24-46-23	29.9	+0.5 to +29.5	19.2[3]	816,100	1
1.25-46-23X	29.9	+0.5 to +29.5	19.2[3]	729,010	1
1.25-46-24	29.9	+0.5 to +29.5	19.2[3]	599,190	1
1.25-46-25	24.1	+0.5 to +23.9	19.2[3]	2,047,000	No Failure
1.25-46-28	36.0	+0.5 to +35.4	34.9[3]	2,101,100	No Failure

*See Section 5.2.3 and Figure 18 for explanation of failure location.

[1]Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened until snug tight (100 ft-lbs).

[2]Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened 1/3 of a turn past snug tight (100 ft-lbs).

[3]A single nut was used on each bar end. Steel spacer sleeves were positioned between the upper and lower load frames so that the full length of bar between end nuts could be preloaded.

TABLE A5

Summary of Fatigue Tests of 1 3/4"ϕ x 27" A307 Anchor Bars

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Anchor Bar Preload (kips)	Total No. of Cycles Tested	Failure* Location
1.75-27-1	36.0	+0.5 to +68.9	0 [1]	56,170	1
1.75-27-2X	36.0	+0.5 to +68.9	0 [1]	70,900	1
1.75-27-3	36.0	+0.5 to +68.9	0 [1]	25,590	1
1.75-27-3X	36.0	+0.5 to +68.9	0 [1]	72,770	1
1.75-27-4	24.1	+0.5 to +46.3	0 [1]	163,140	1
1.75-27-5	24.1	+0.5 to +46.3	0 [1]	125,360	1
1.75-27-5X	24.1	+0.5 to +46.3	0 [1]	278,460	1
1.75-27-6	24.1	+0.5 to +46.3	0 [1]	202,080	1
1.75-27-6X	24.1	+0.5 to +46.3	0 [1]	474,690	1
1.75-27-7	11.9	+0.5 to +23.1	0 [1]	2,709,000	No Failure
1.75-27-8	11.9	+0.5 to +23.1	0 [1]	3,555,400	No Failure
1.75-27-9	36.0	+0.5 to +68.9	0 [2]	76,360	2
1.75-27-10	36.0	+0.5 to +68.9	0 [2]	177,200	4
1.75-27-11	36.0	+0.5 to +68.9	0 [2]	160,460	2
1.75-27-12	36.0	+0.5 to +68.9	0 [2]	68,930	2
1.75-27-30	30.0	+0.5 to +57.5	0 [2]	595,200	4
1.75-27-31	30.0	+0.5 to +57.5	0 [2]	1,197,250	3
1.75-27-32	30.0	+0.5 to +57.5	0 [2]	1,279,930	3
1.75-27-13	24.1	+0.5 to +46.3	0 [2]	2,188,850	No Failure
1.75-27-14	24.1	+0.5 to +46.3	0 [2]	2,330,000	No Failure
1.75-27-15X	36.0	+0.5 to +68.9	37.6 [3]	145,680	1
1.75-27-16	36.0	+0.5 to +68.9	37.6 [3]	41,900	1
1.75-27-17	36.0	+0.5 to +68.9	37.6 [3]	218,460	1
1.75-27-22	36.0	+0.5 to +68.9	37.6 [3]	221,750	1
1.75-27-23	36.0	+0.5 to +68.9	37.6 [3]	188,790	1
1.75-27-25	32.0	+0.5 to +61.3	37.6 [3]	58,420	1
1.75-27-26	32.0	+0.5 to +61.3	37.6 [3]	117,420	1
1.75-27-27	32.0	+0.5 to +61.3	37.6 [3]	299,960	1

TABLE A5 (Continued)

Summary of Fatigue Tests of 1 3/4" x 27" A307 Anchor Bars

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Anchor Bar Preload (kips)	Total No. of Cycles Tested	Failure* Location
1.75-27-24	30.0	+0.5 to +57.5	37.6 [3]	1,085,670	1
1.75-27-28	30.0	+0.5 to +57.5	37.6 [3]	138,390	1
1.75-27-29	30.0	+0.5 to +57.5	37.6 [3]	122,160	1
1.75-27-33	27.0	+0.5 to +51.8	37.6 [3]	1,178,110	1
1.75-27-34	27.0	+0.5 to +51.8	37.6 [3]	1,626,490	1
1.75-27-18	24.1	+0.5 to +46.3	37.6 [3]	2,012,000	No Failure
1.75-27-19	24.1	+0.5 to +46.3	37.6 [3]	2,081,000	No Failure
1.75-27-20	36.0	+0.5 to +68.9	68.4 [3]	2,458,000	No Failure
1.75-27-21	36.0	+0.5 to +68.9	68.4 [3]	2,571,000	No Failure

*See Section 5.2.3 and Figure 18 for explanation of failure location.

[1] Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened until snug tight (100 ft-lbs).

[2] Two nuts were placed on each end of the anchor bars tested, one leveling nut beneath the load plate and an outer nut which was tightened. The outside nuts at each end of the bars were tightened 1/3 of a turn past snug tight (100 ft-lbs).

[3] A single nut was used on each bar end. Steel spacer sleeves were positioned between the upper and lower load frames so that the full length of bar between end nuts could be preloaded.

TABLE A6

Summary of Fatigue Tests of 5/8"ϕ x 1 3/4" A325 Capscrews

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Capscrew Preload	Total No. of Cycles Tested	Failure Mode
5/8 CS-25 & 26	86.6	+0.5 to +39.7	1	2,852	26 fractured 25 cracked
5/8 CS-25A & 26A	86.6	+0.5 to +39.7	1	2,177	25A fractured 26A cracked & bent
5/8 CS-25B & 26B	86.6	+0.5 to +39.7	1	3,488	26B fractured 25B cracked & bent
5/8 CS-25C & 26C	86.6	+0.5 to +39.7	1	3,137	25C fractured 26C cracked & bent
5/8 CS-27 & 28	61.5	+0.5 to +28.3	1	9,322	28 fractured 27 cracked
5/8 CS-27A & 28A	61.5	+0.5 to +28.3	1	9,806	28A fractured 27A cracked
5/8 CS-27B & 28B	61.5	+0.5 to +28.3	1	12,293	28B fractured 27B cracked & bent
5/8 CS-27C & 28C	61.5	+0.5 to +28.3	1	13,981	28C fractured 27C cracked & bent
5/8 CS-29 & 30	30.4	+0.5 to +14.2	1	1,128,690	29 fractured 30 no damage
5/8 CS-29A & 30A	30.4	+0.5 to +14.2	1	514,580	29A fractured 30A cracked
5/8 CS-29B & 30B	30.4	+0.5 to +14.2	1	301,100	30B fractured 29B cracked
5/8 CS-29C & 30C	30.4	+0.5 to +14.2	1	2,647,000	No failure
5/8 CS-29D & 30D	30.4	+0.5 to +14.2	1	2,160,000	No failure

TABLE A6 (Continued)

Summary of Fatigue Tests of 5/8"ϕ x 1 3/4" A325 Capscrews

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Capscrew Preload	Total No. of Cycles Tested	Failure Mode
5/8 CS- 31 & 32	9.2	+0.5 to + 4.7	1	2,082,000	No failure
5/8 CS- 17 & 18	86.6	+0.5 to +39.7	2	7,830	17 fractured 18 cracked
5/8 CS- 17A & 18A	86.6	+0.5 to +39.7	2	3,805	18A fractured 17A cracked & bent
5/8 CS- 23 & 24	86.6	+0.5 to +39.7	2	6,584	24 fractured 23 cracked
5/8 CS- 23A & 24A	86.6	+0.5 to +39.7	2	7,177	24A fractured 23A cracked and bent
5/8 CS- 33 & 34	74.1	+0.5 to +34.0	2	17,283	34 fractured 33 cracked and bent
5/8 CS- 33A & 34A	74.1	+0.5 to +34.0	2	27,750	33A fractured 34A cracked & bent
5/8 CS- 33B & 34B	74.1	+0.5 to +34.0	2	18,505	34B fractured 33B cracked & bent
5/8 CS- 33C & 34C	74.1	+0.5 to +34.0	2	28,040	33C fractured 34C cracked and bent
5/8 CS- 13 & 14	61.5	+0.5 to +28.3	2	217,604	14 fractured 13 bent
5/8 CS- 13A & 14A	61.5	+0.5 to +28.3	2	126,234	14A fractured 13A bent
5/8 CS- 15 & 16	61.5	+0.5 to +28.3	2	262,688	15 fractured 16 bent
5/8 CS- 15A & 16A	61.5	+0.5 to +28.3	2	304,322	15A fractured 16A no damage

TABLE A6 (Continued)

Summary of Fatigue Tests of 5/8"ϕ x 1 3/4" A325 Capscrews

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Capscrew Preload	Total No. of Cycles Tested	Failure Mode
5/8 CS-19 & 20	30.4	+0.5 to +14.2	2	2,018,000	No failure
5/8 CS-21 & 22	30.4	+0.5 to +14.2	2	2,147,000	No failure
5/8 CS-9 & 10	9.2	+0.5 to + 4.7	2	2,129,015	No failure
5/8 CS-11 & 12	9.2	+0.5 to + 4.7	2	2,129,015	No failure

1 Capscrews were tightened until snug tight (80 ft-lbs).

2 Capscrews were tightened 1/3 of a turn past snug tight (80 ft-lbs).

TABLE A7

Summary of Fatigue Tests of 1"ϕ x 2 1/2" A325 Capscrews

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Capscrew Preload	Total No. of Cycles Tested	Failure Mode
1CS- 1 & 2	86.6	+0.5 to +105.5	1	1,271	1 fractured 2 no damage
1CS- 1A & 2A	86.6	+0.5 to +105.5	1	1,420	1A fractured 2A no damage
1CS- 1B & 2B	86.6	+0.5 to +105.5	1	1,474	1B fractured 2B bent
1CS- 1C & 2C	86.6	+0.5 to +105.5	1	1,324	1C fractured 2C bent & cracked
1CS- 3 & 4	61.6	+0.5 to +75.2	1	5,802	4 fractured 3 no damage
1CS- 3A & 4A	61.6	+0.5 to +75.2	1	4,345	4A fractured 3A no damage
1CS- 3B & 4B	61.6	+0.5 to +75.2	1	5,200	3B fractured 4B no damage
1CS- 5 & 6	30.4	+0.5 to +37.3	1	45,525	5 fractured 6 bent & cracked
1CS- 5A & 6A	30.4	+0.5 to +37.3	1	41,804	5A fractured 6A no damage
1CS- 5B & 6B	30.4	+0.5 to +37.3	1	34,664	5B fractured 6B no damage
1CS- 5C & 6C	30.4	+0.5 to +37.3	1	47,260	6C fractured 5C cracked
1CS- 7 & 8	9.2	+0.5 to +11.7	1	2,823,010	7 fractured 8 fractured
1CS- 9 & 10	86.6	+0.5 to +105.5	2	2,890	9 fractured 10 bent & cracked

TABLE A7 (Continued)

Summary of Fatigue Tests of 1"ϕ x 2 1/2" A325 Capscrews

Specimen No.	Externally Applied Stress Range (ksi)	Externally Applied Load Range (kips)	Capscrew Preload	Total No. of Cycles Tested	Failure Mode
1CS- 9A & 10A	86.6	+0.5 to +105.5	2	1,408	9A fractured 10A no damage
1CS- 9B & 10B	86.6	+0.5 to +105.5	2	2,381	9B fractured 10B cracked
1CS- 9C & 10C	86.6	+0.5 to +105.5	2	2,124	9C fractured 10C cracked
1CS- 11 & 12	61.6	+0.5 to +75.2	2	54,965	12 fractured 11 no damage
1CS- 11A & 12A	61.6	+0.5 to +75.2	2	59,484	11A fractured 12A cracked
1CS- 11B & 12B	61.6	+0.5 to +75.2	2	72,490	11B cracked 12B fractured
1CS- 11C & 12C	61.6	+0.5 to +75.2	2	51,710	11C fractured 12C cracked
1CS- XA & XB	49.6	+0.5 to +60.6	2	400,000	XA fractured XB no damage
1CS- X1 & X2	49.6	+0.5 to +60.6	2	2,040,000	No failure
1CS- X3 & X4	49.6	+0.5 to +60.6	2	2,064,000	No failure
1CS- 13 & 14	30.4	+0.5 to +37.3	2	2,414,000	No failure
1CS- 13A & 14A	30.4	+0.5 to +37.3	2	2,312,770	No failure

1 Capscrews were tightened until snug tight (80 ft-lbs).

2 Capscrews were tightened 1/3 of a turn past snug tight (80 ft-lbs).

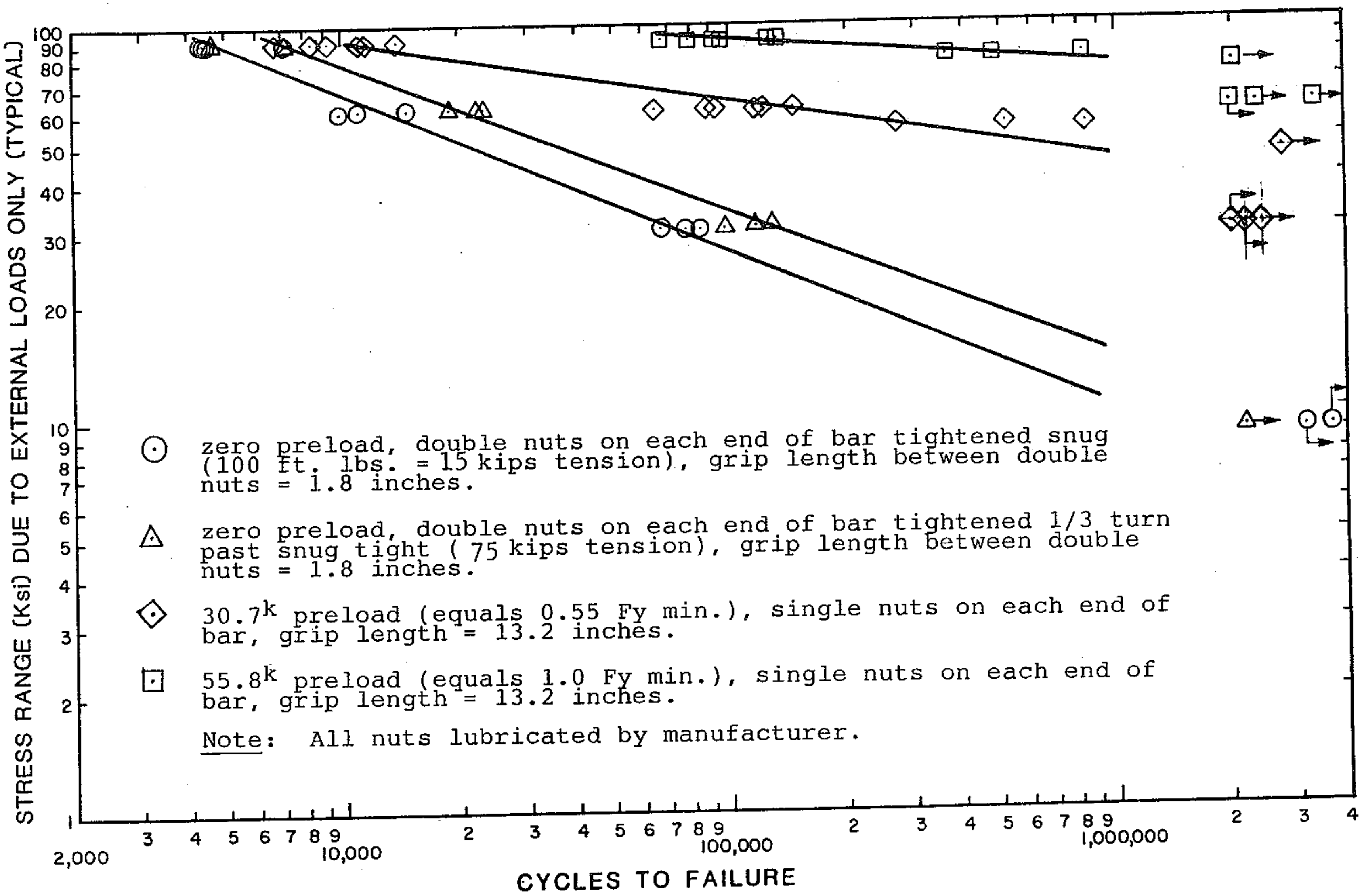

Figure B1. Effect of preload on fatigue life of 1"Ø x 16" ASTM A449 anchor bars.

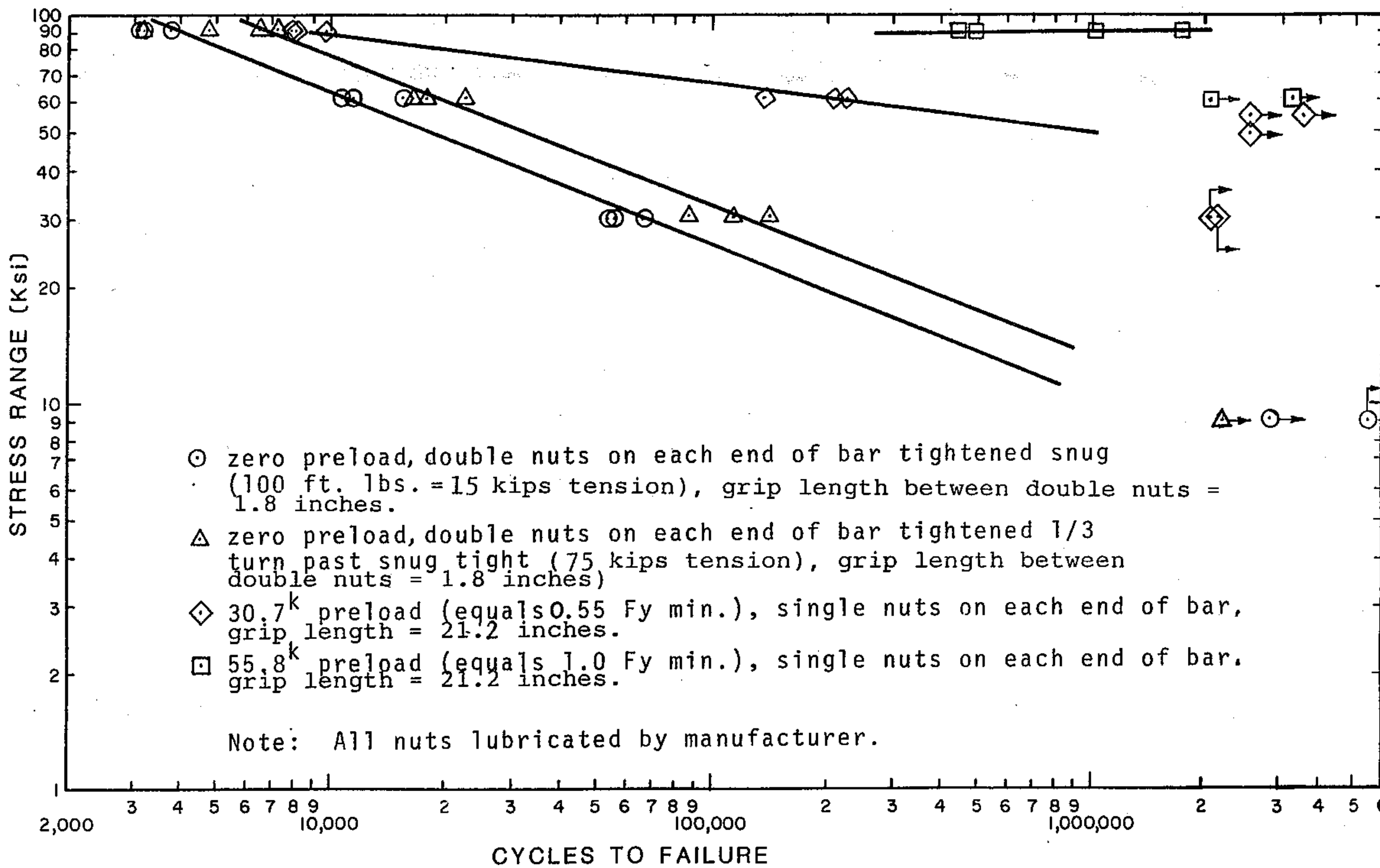

Figure B2. Effect of preload on fatigue life of 1"Ø x 24" ASTM A449 anchor bars.

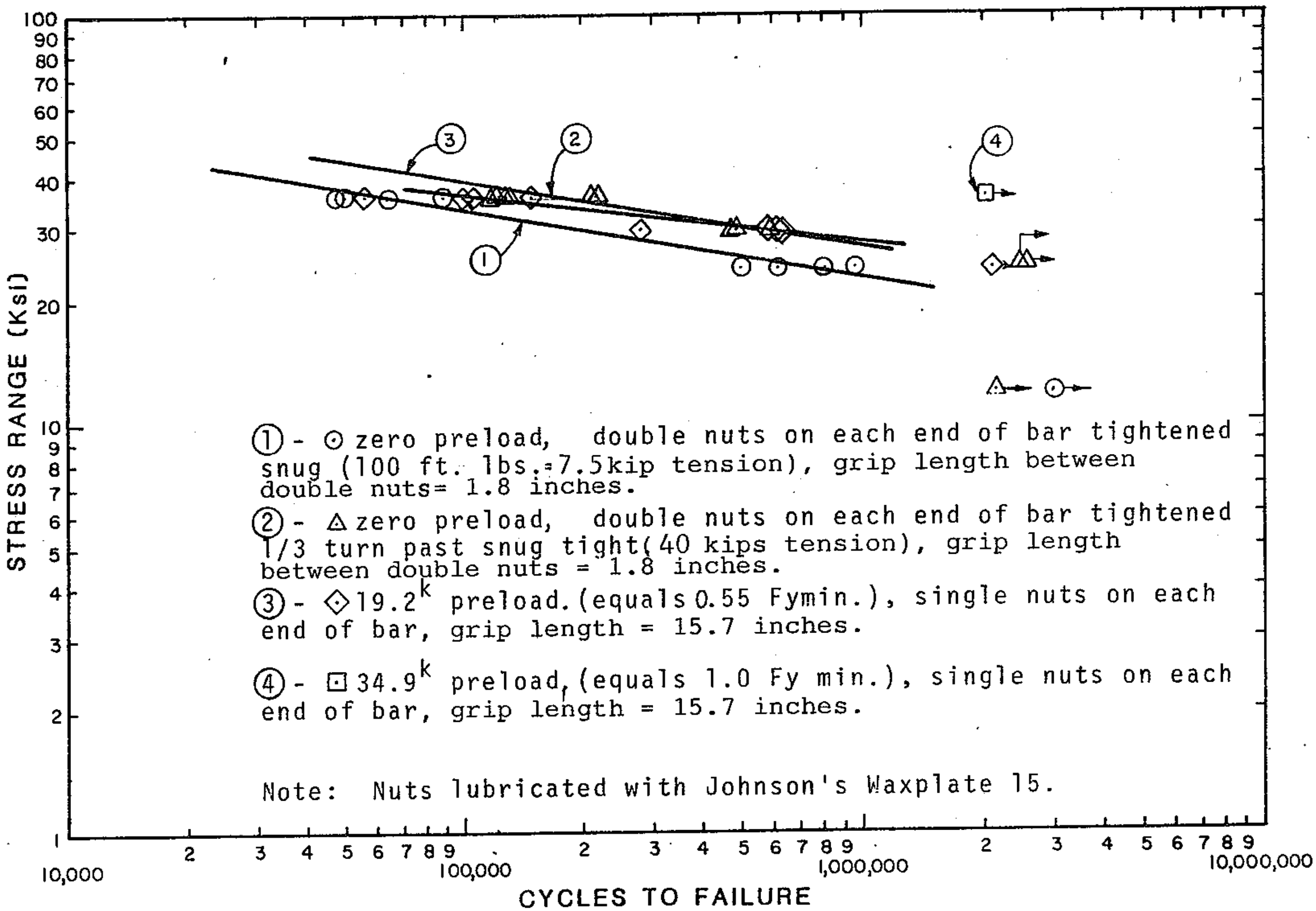

Figure B3. Effect of preload on fatigue life of 1¼"Ø x 19" ASTM A307 anchor bars.

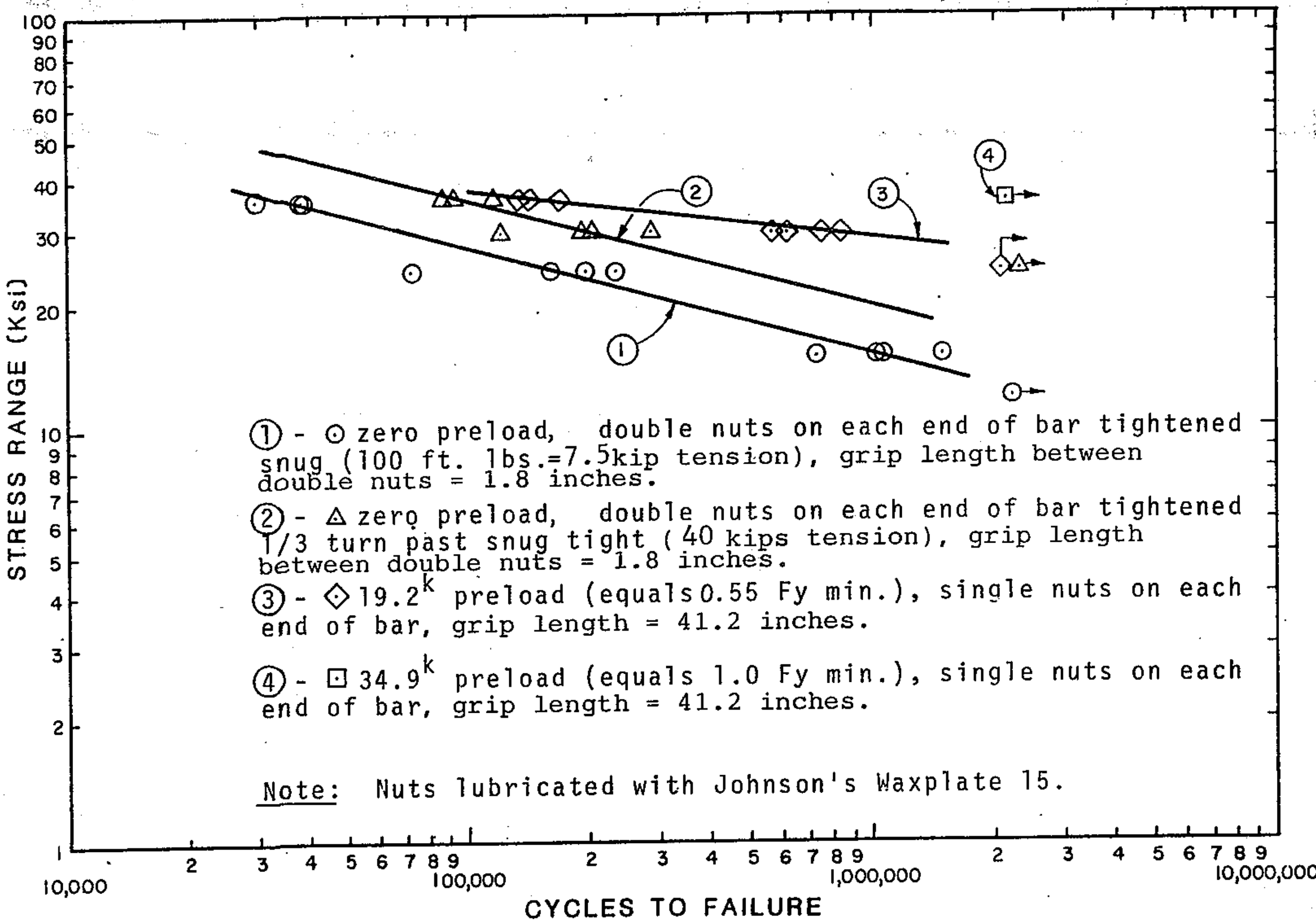

Figure B4. Effect of preload on fatigue life of 1¼"Ø x 46" ASTM A307 anchor bars.

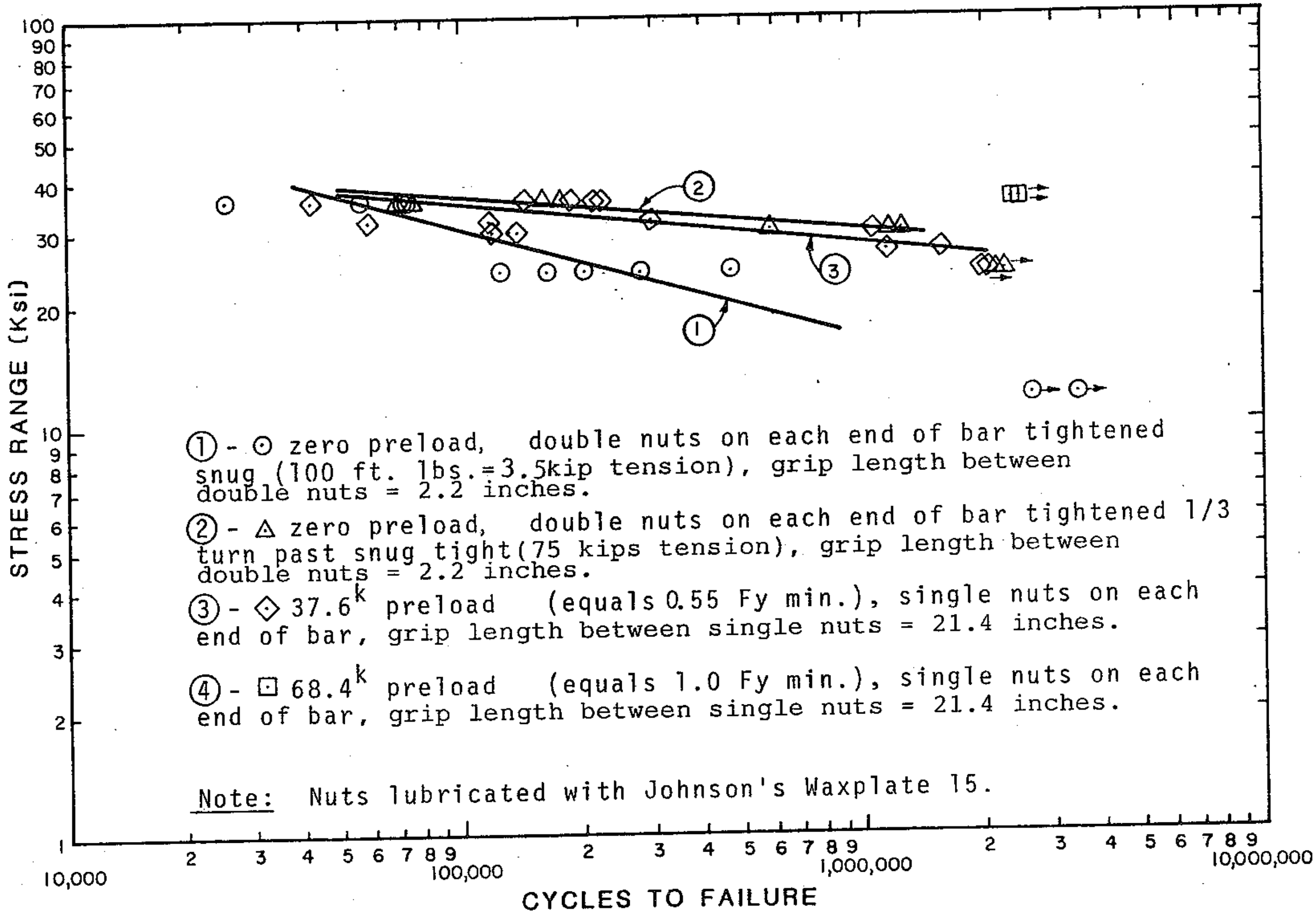

Figure B5. Effect of preload on fatigue life of 1 3/4"Ø x 27" ASTM A307 anchor bars.

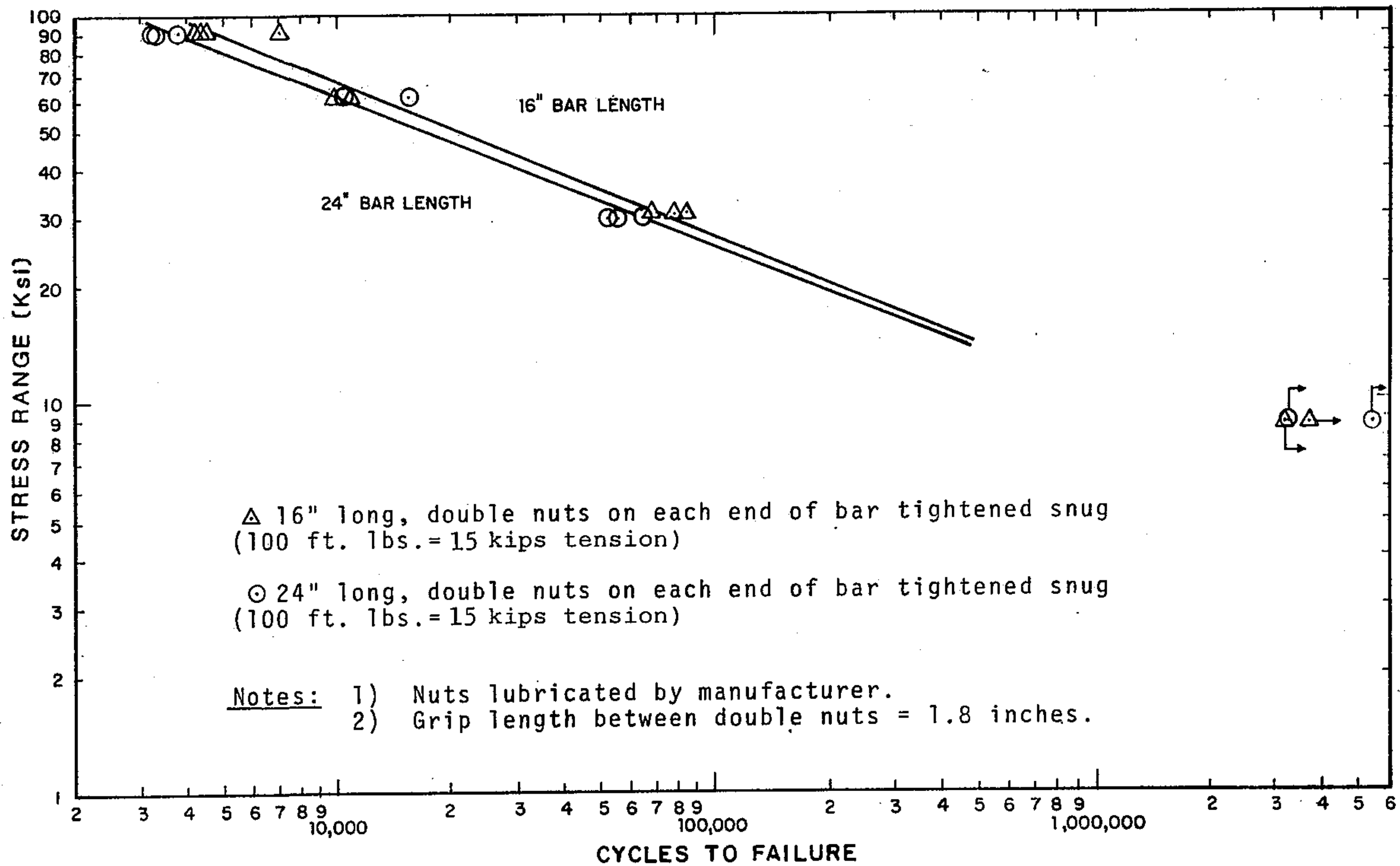

Figure B6. Effect of bar length on fatigue life of 1"Ø ASTM A449 Anchor bars with double nuts, snug tight only.

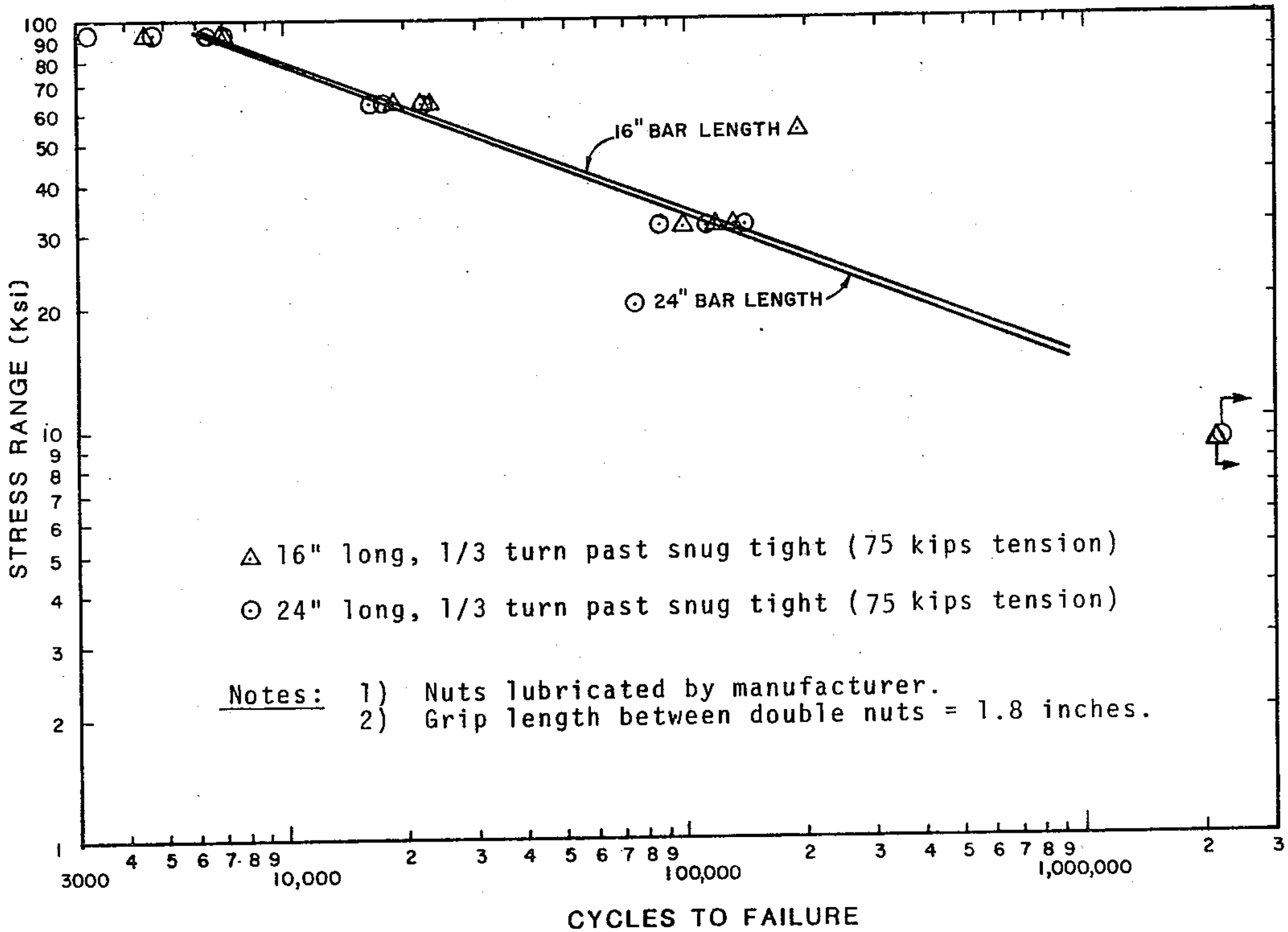

Figure B7. Effect of bar length on fatigue life of 1"Ø ASTM A449 anchor bars with double nuts tightened to snug + 1/3 turn.

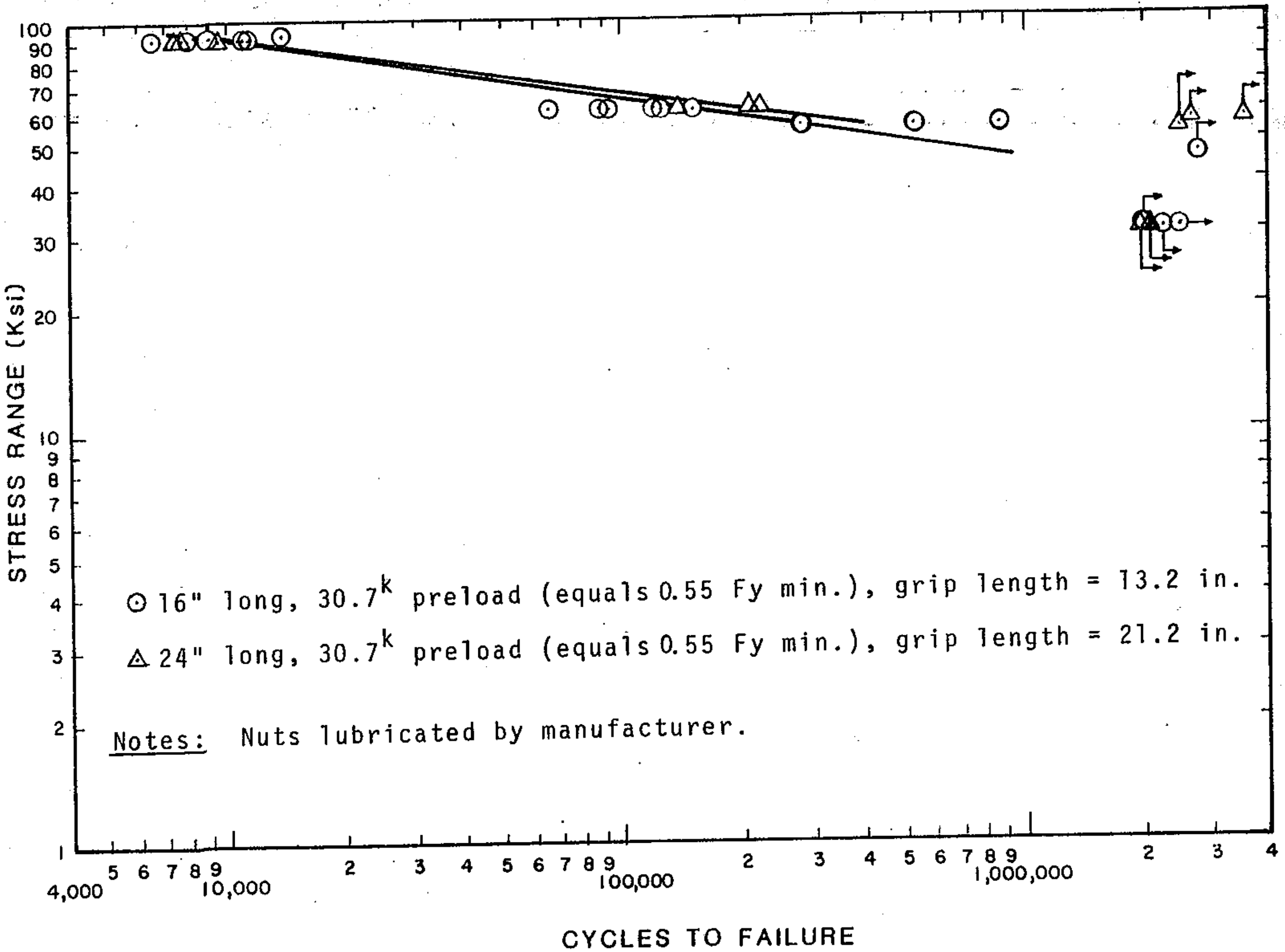

Figure B8. Effect of preloaded bar length on fatigue life of 1"Ø ASTM A449 anchor bars with single nuts.

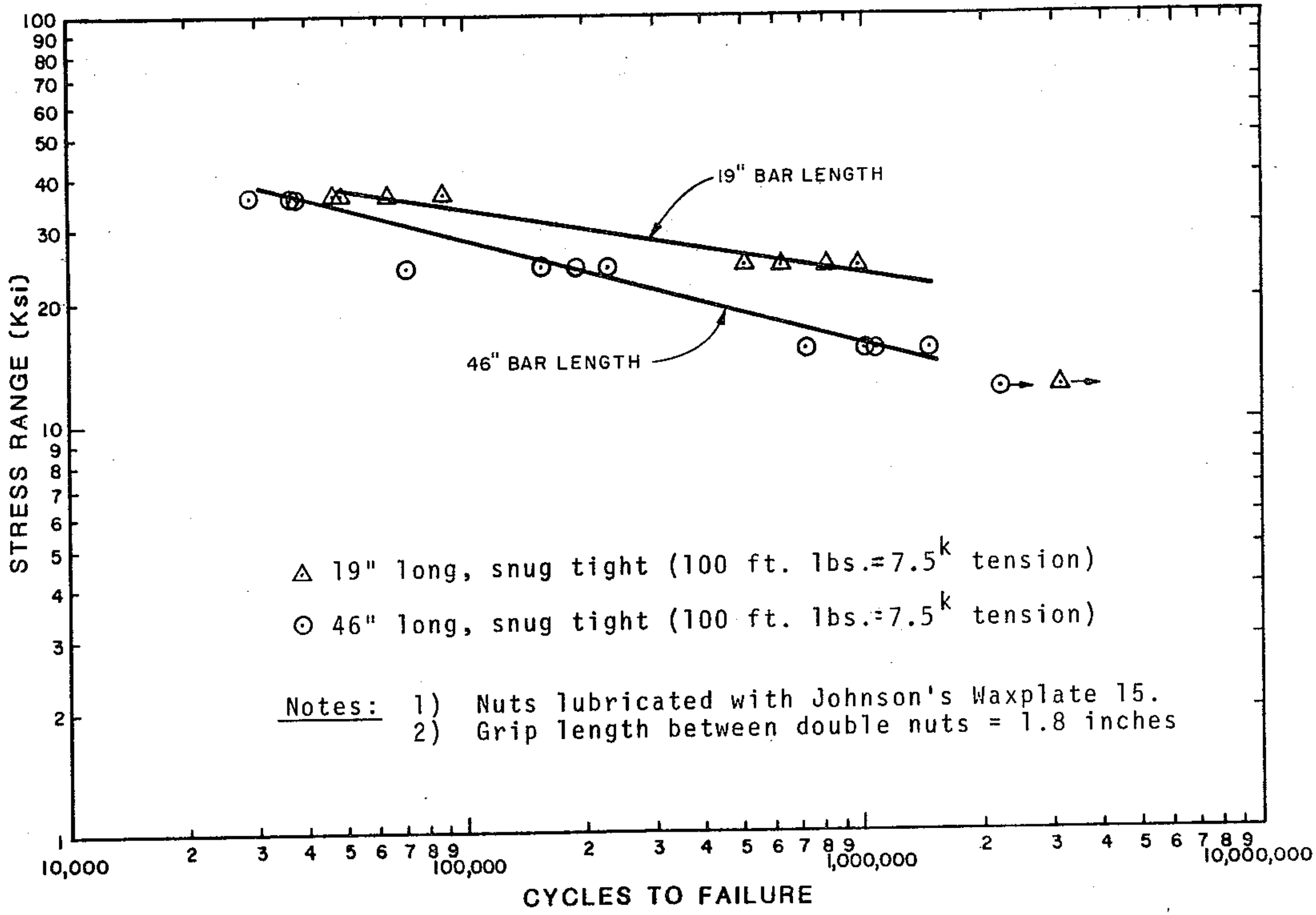

Figure B9. Effect of bar length on fatigue life of 1¼"Ø ASTM A307 anchor bars with double nuts, snug tight only.

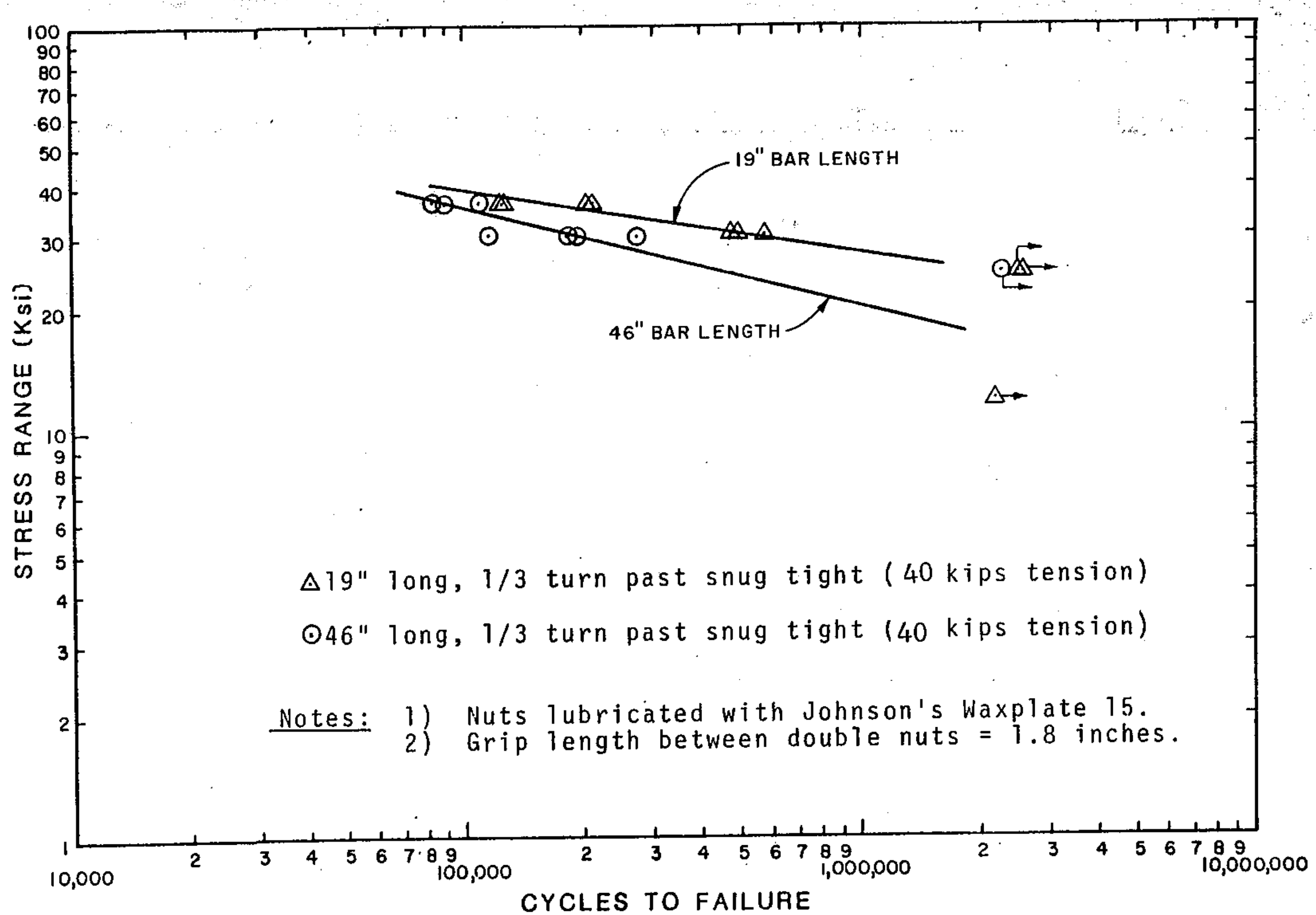

Figure B10. Effect of bar length on fatigue life of 1¼"Ø ASTM A307 anchor bars with double nuts tightened 1/3 turn past snug tight.

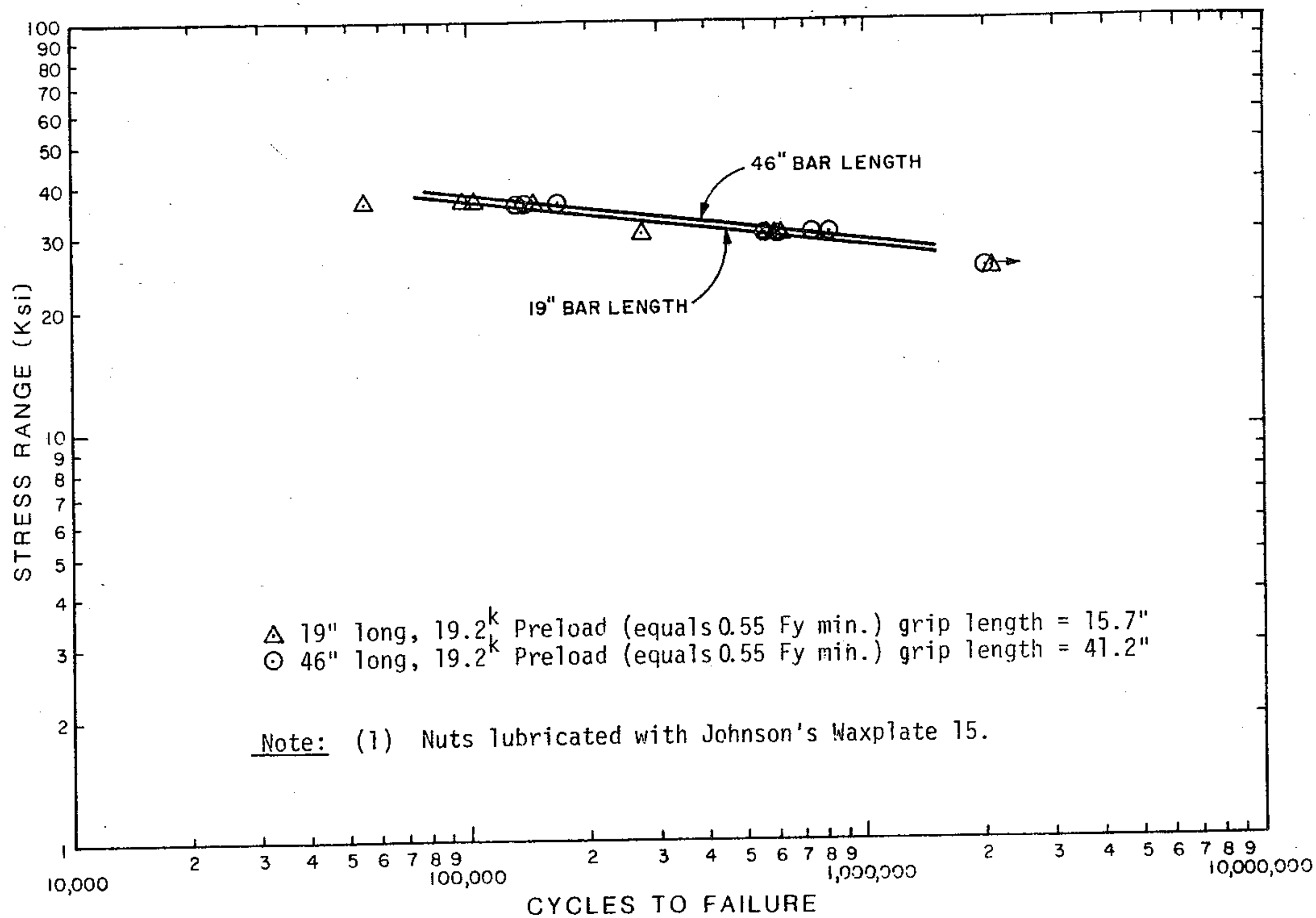

Figure B11. Effect of preloaded bar length on fatigue life of 1¼"Ø ASTM A307 anchor bars with single nuts.

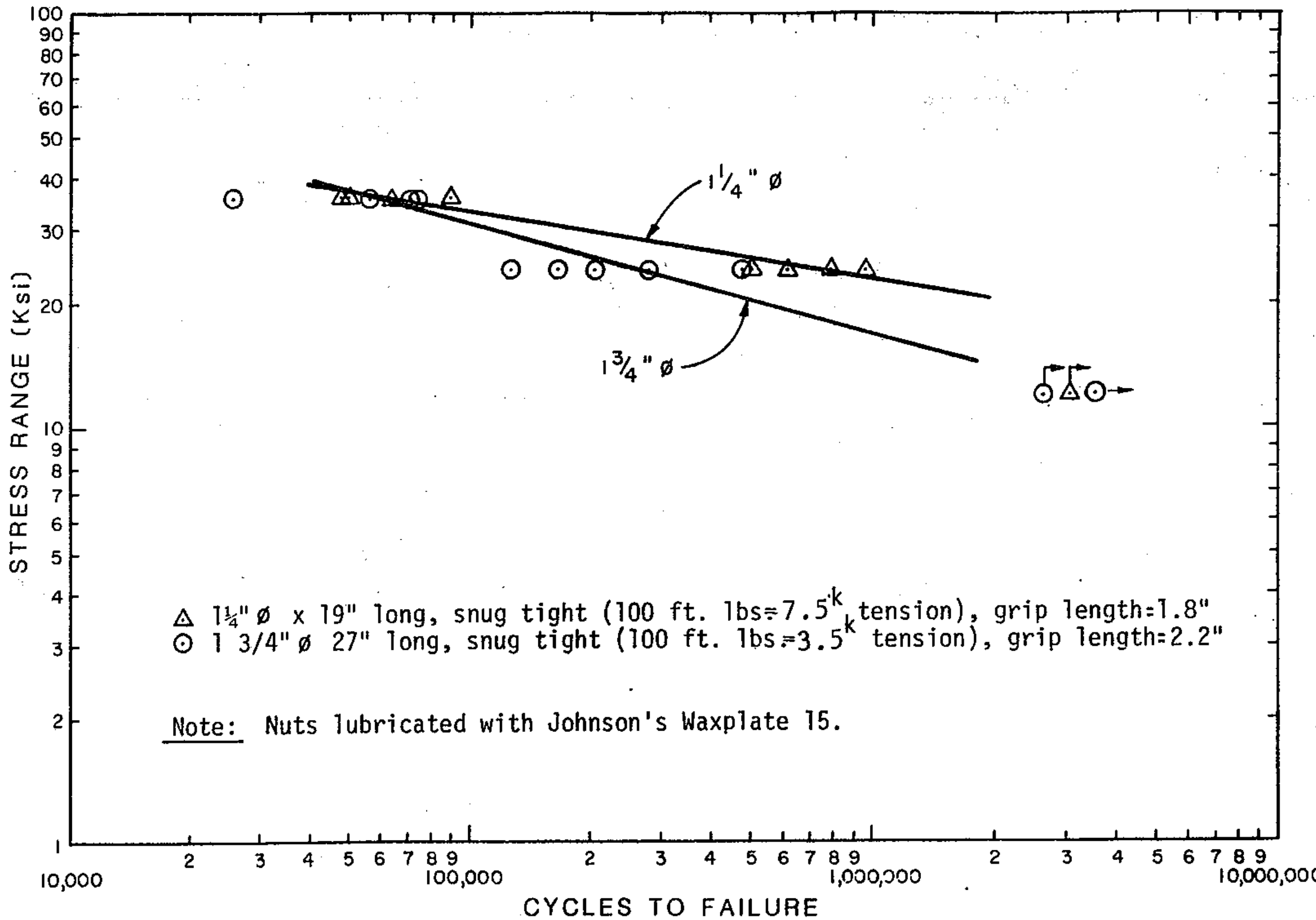

Figure B12. Effect of bar diameter on fatigue life of short ASTM A307 anchor bars with double nuts snug tight only.

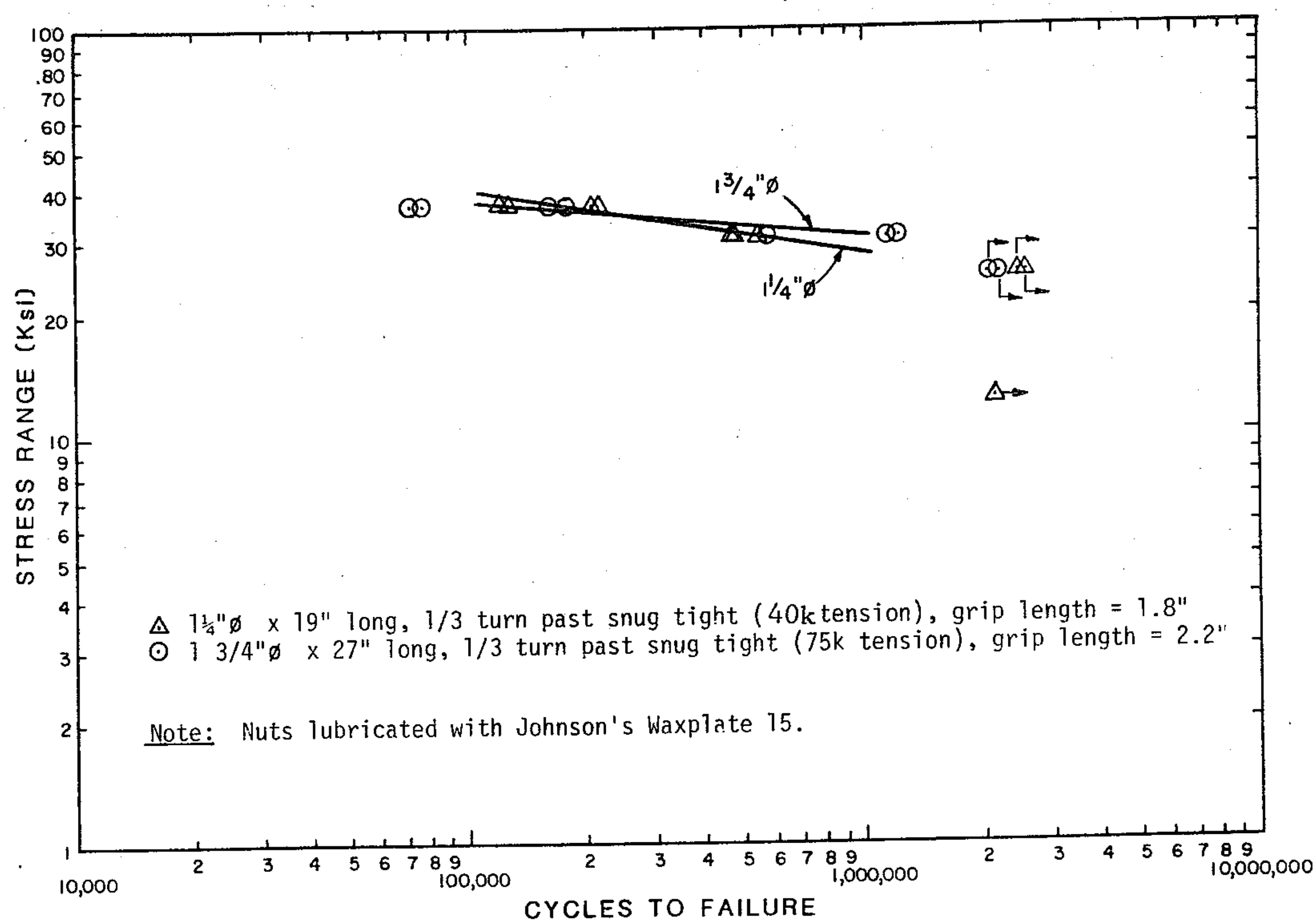

Figure B13. Effect of bar diameter on fatigue life of short ASTM A307 anchor bars with double nuts tightened to 1/3 turn past snug tight.

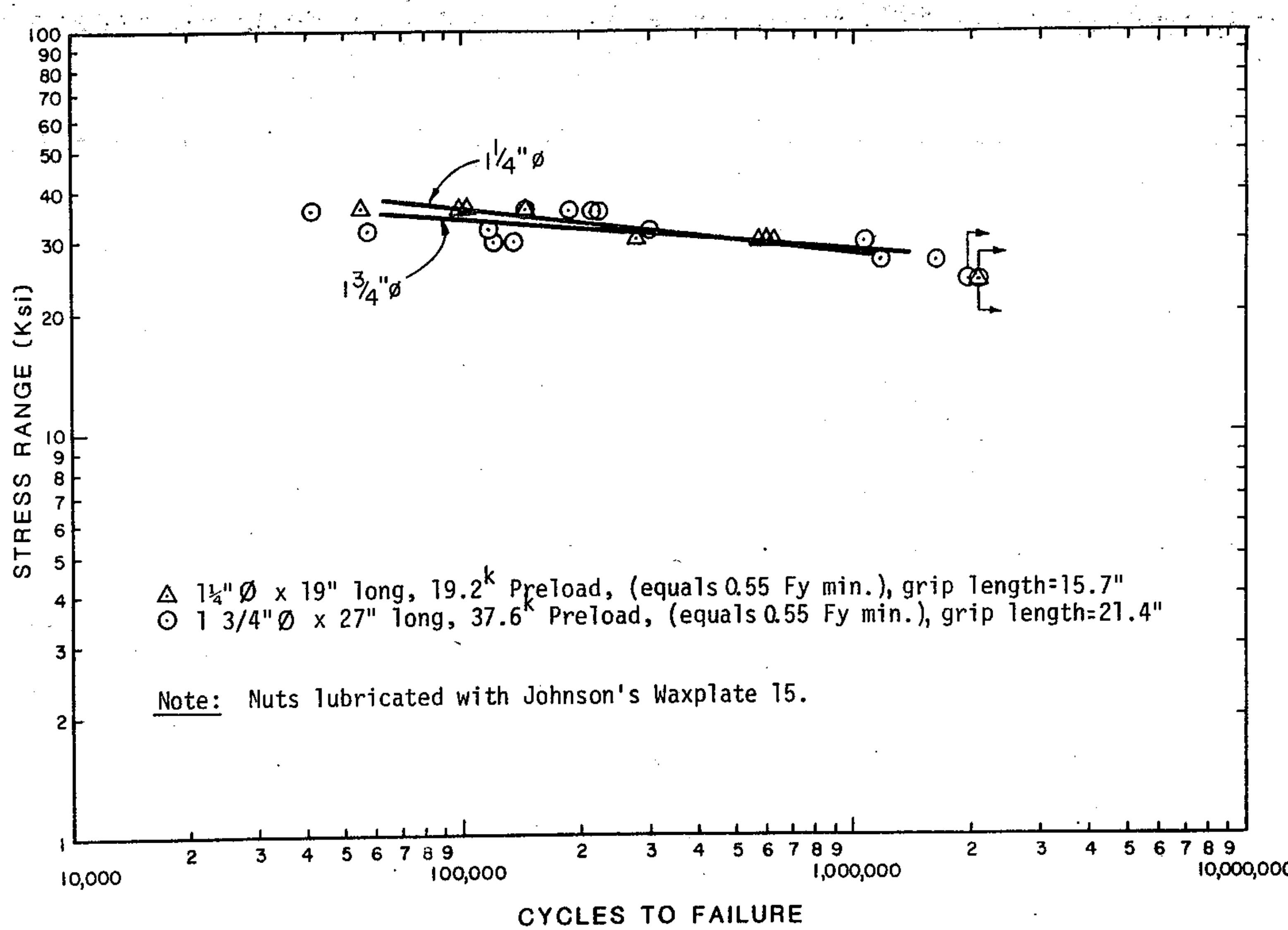

Figure B14. Effect of bar diameter on fatigue life of short preloaded ASTM A307 anchor bars with single nuts.

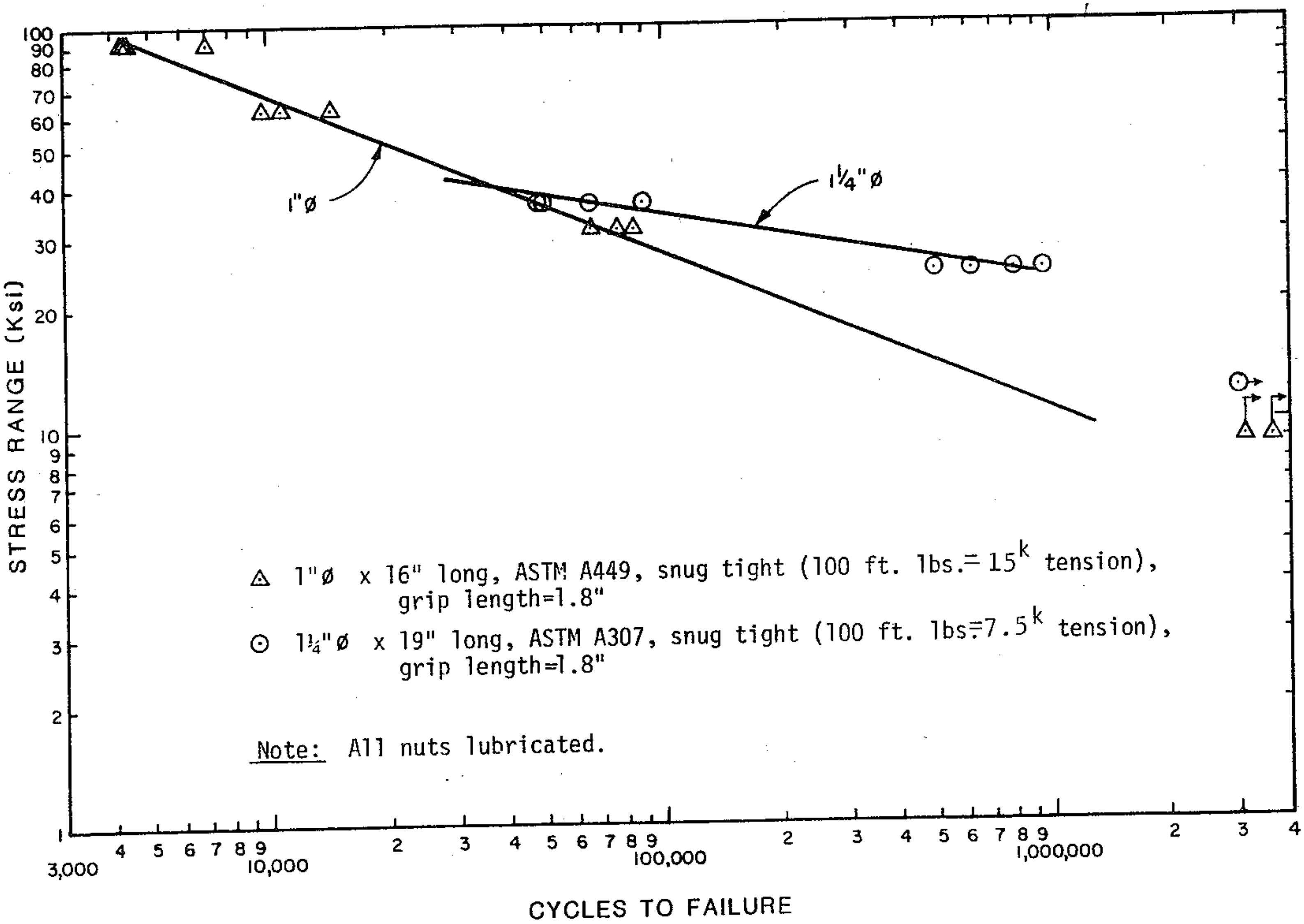

Figure B15. Effect of steel type on fatigue life of short anchor bars with double nuts, snug tight only.

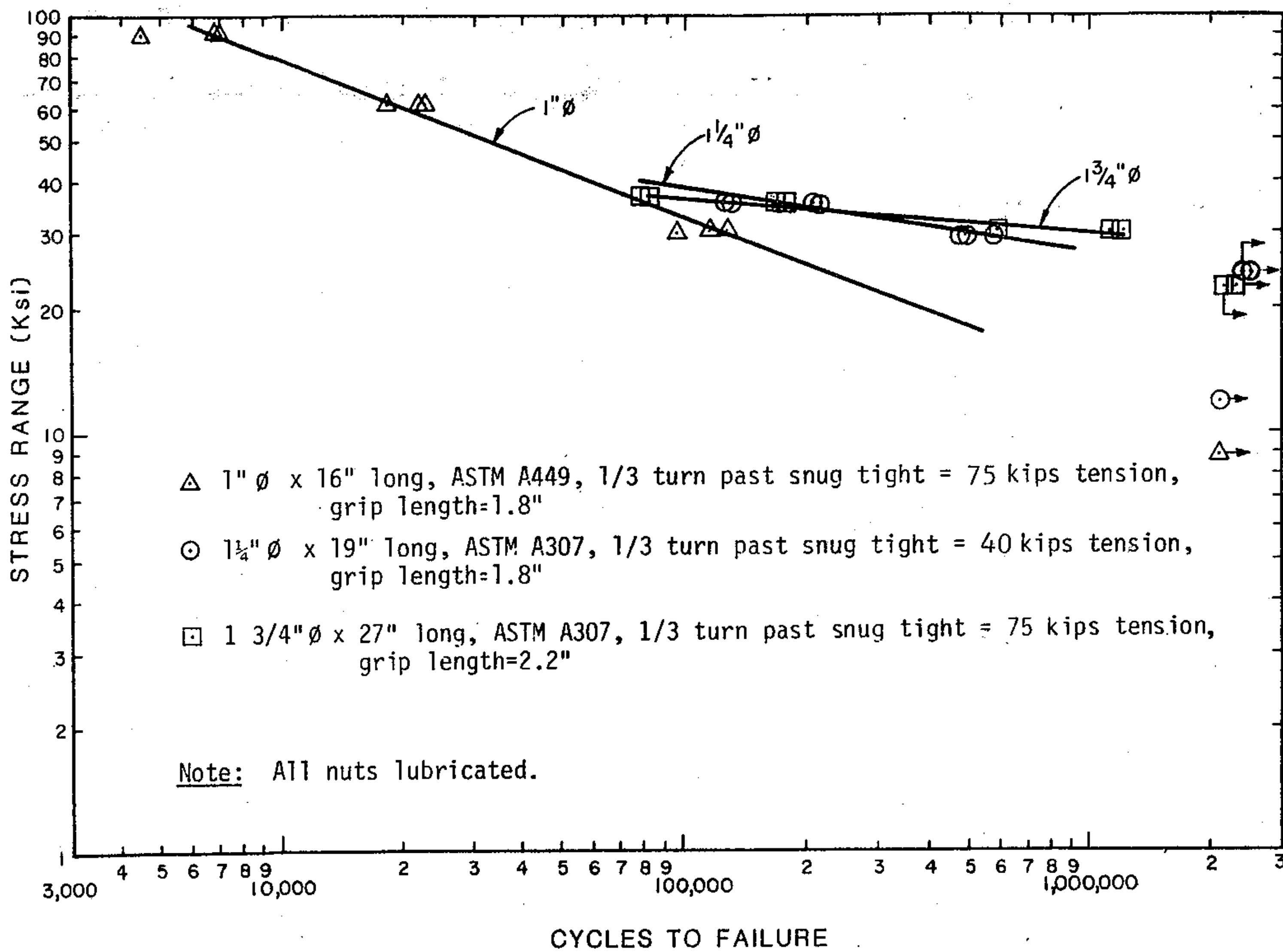

Figure B16. Effect of steel type on fatigue life of short anchor bars with double nuts tightened 1/3 turn past snug tight.

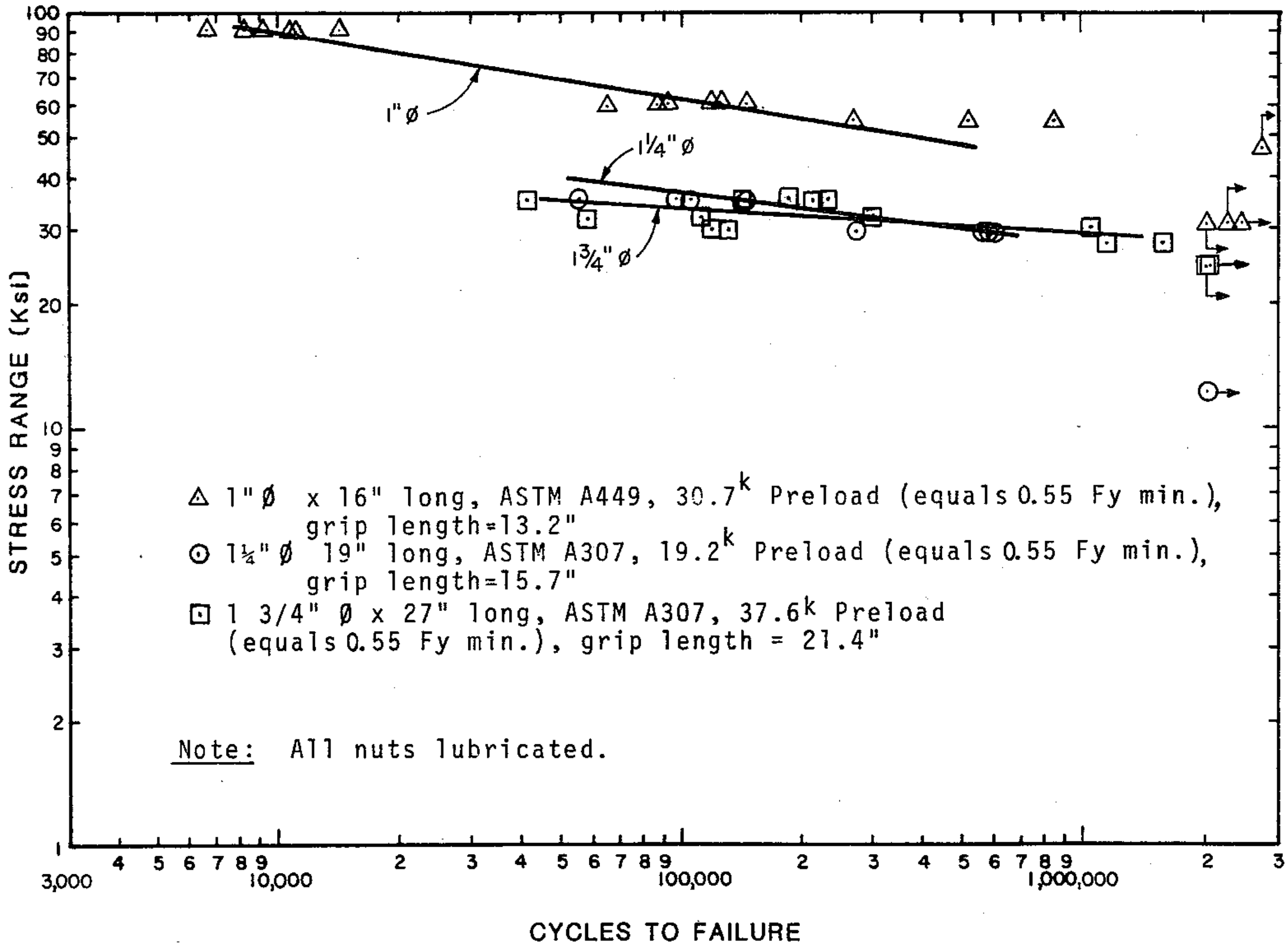

Figure B17. Effect of steel type on fatigue life of short preloaded anchor bars with single nuts.

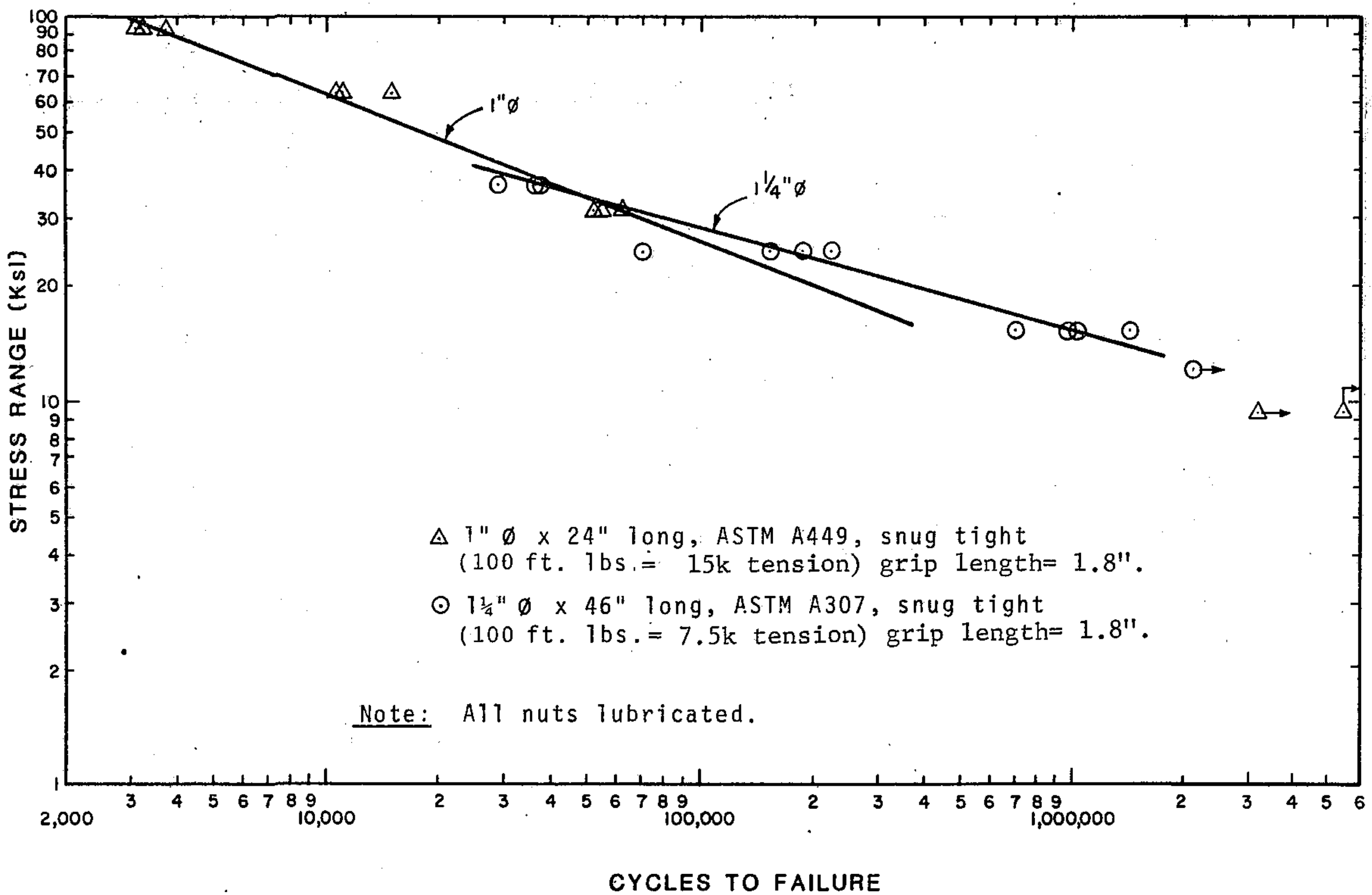

Figure B18. Effect of steel type on fatigue life of long anchor bars with double nuts, snug tight only.

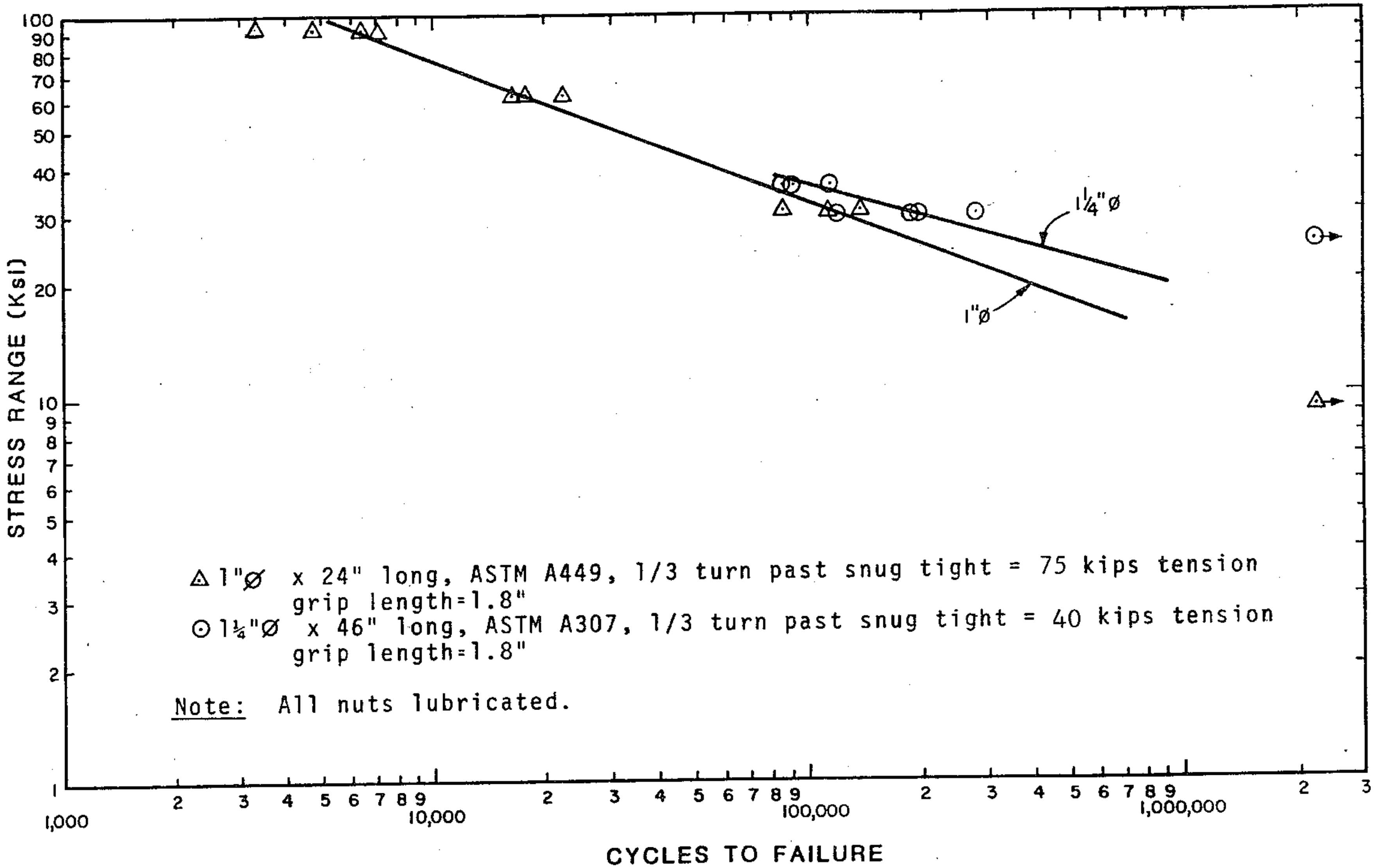

Figure B19. Effect of steel type on fatigue life of long anchor bars with double nuts tightened 1/3 turn past snug tight.

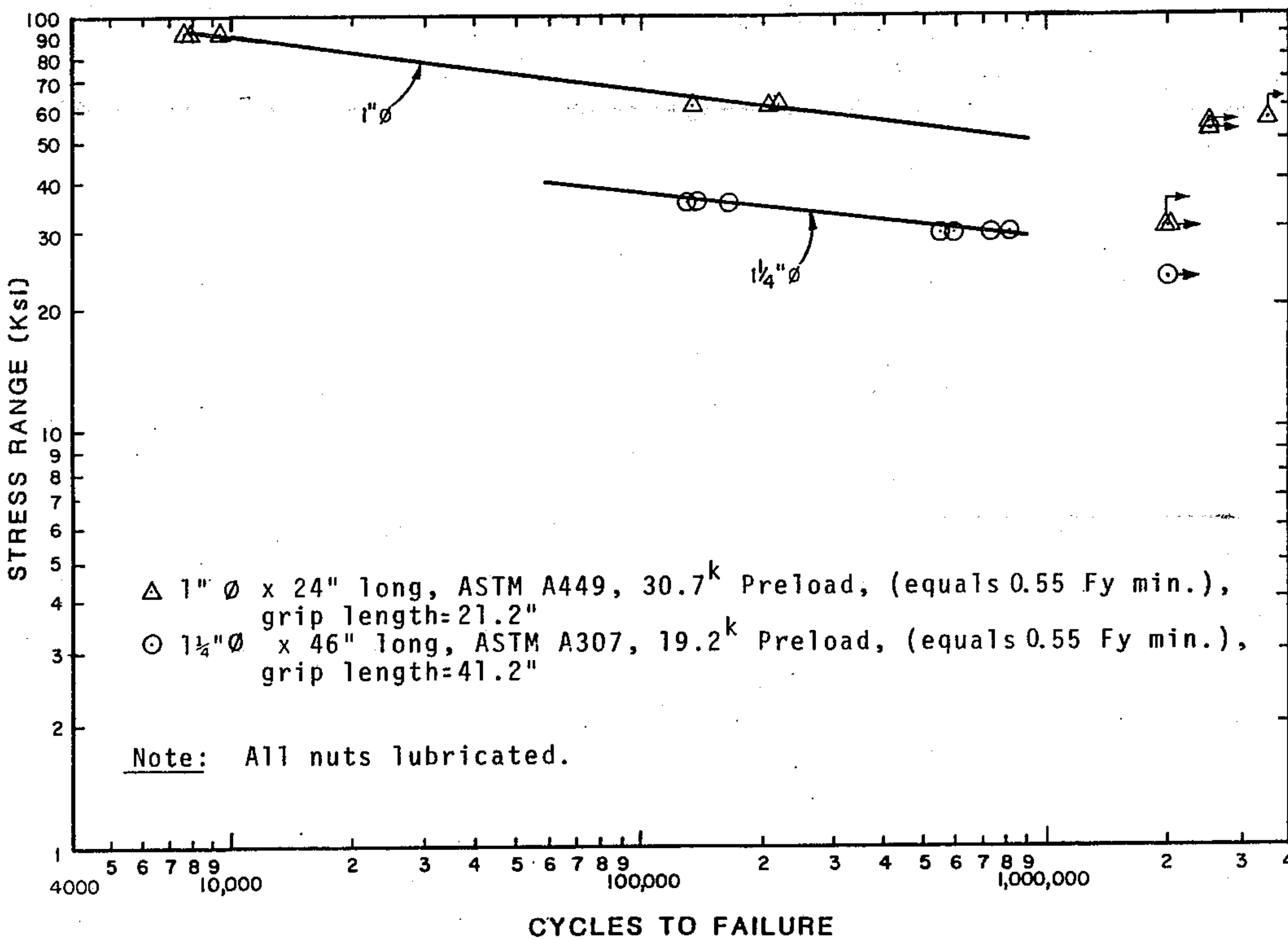

Figure B20. Effect of steel type on fatigue life of long preloaded anchor bars with single nuts.

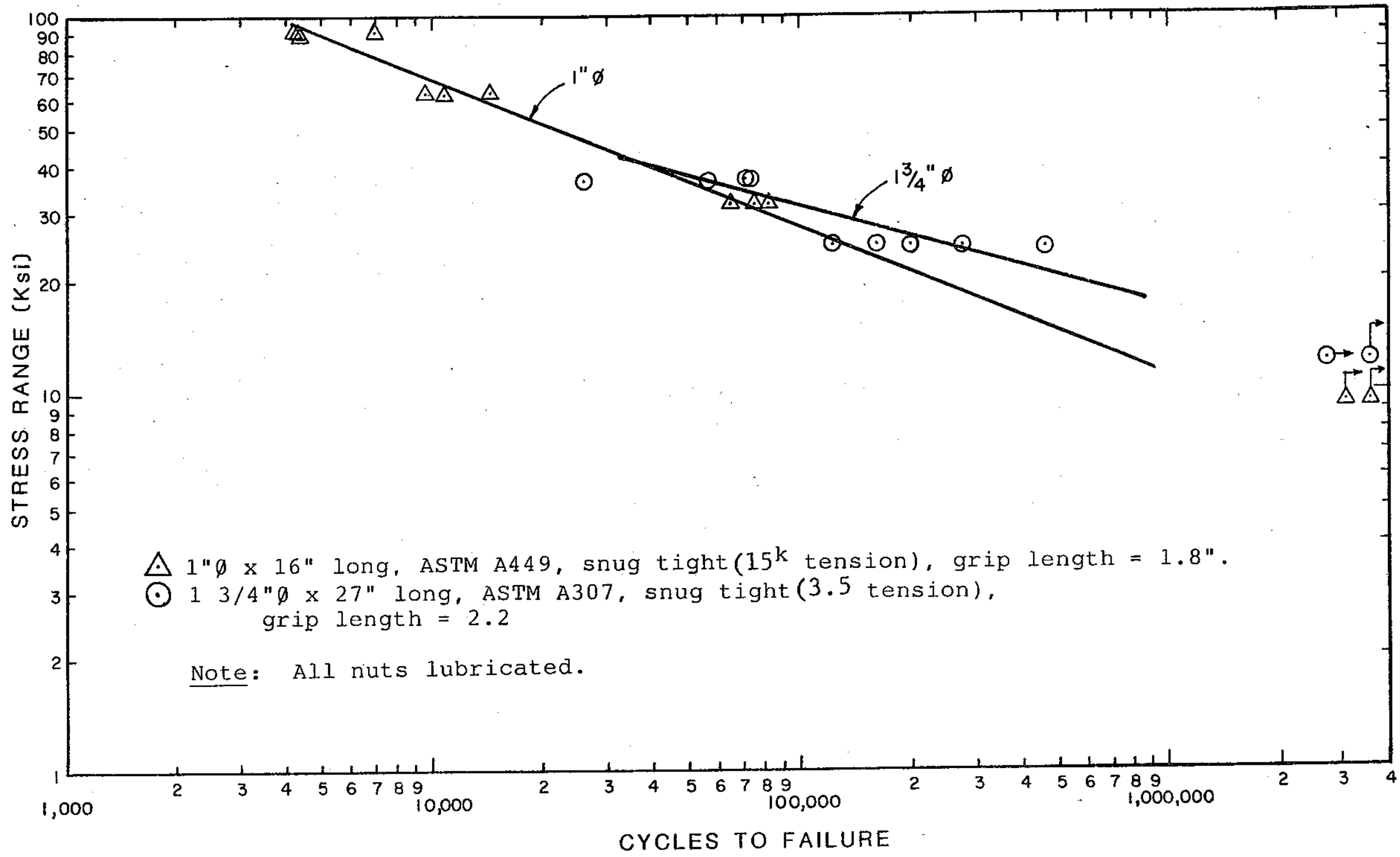

Figure B21. Effect of steel type on fatigue life of anchor bars with double nuts, snug tight only.

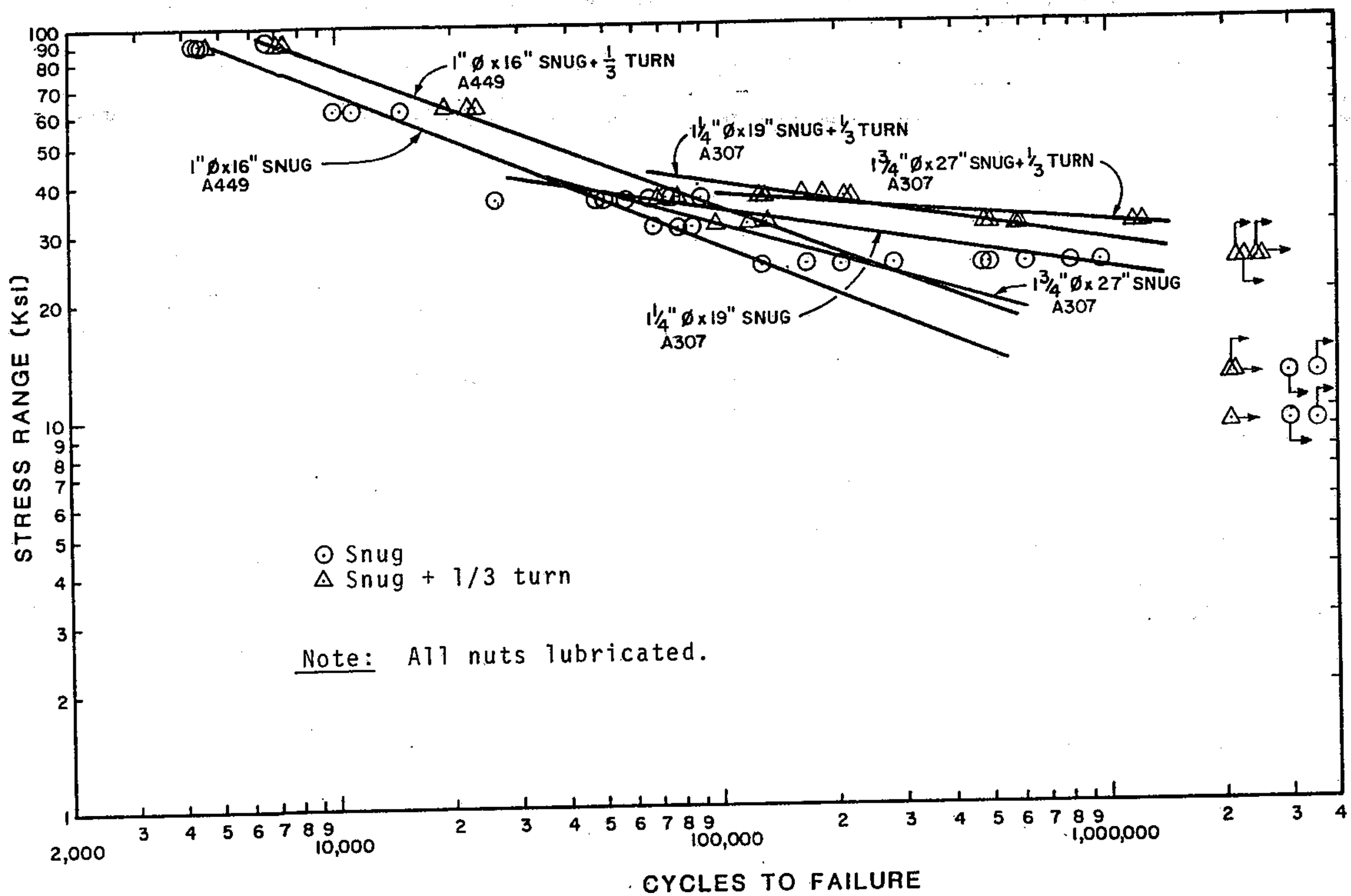

Figure B22. Effect of tightening double nuts on fatigue life of short anchor bars.

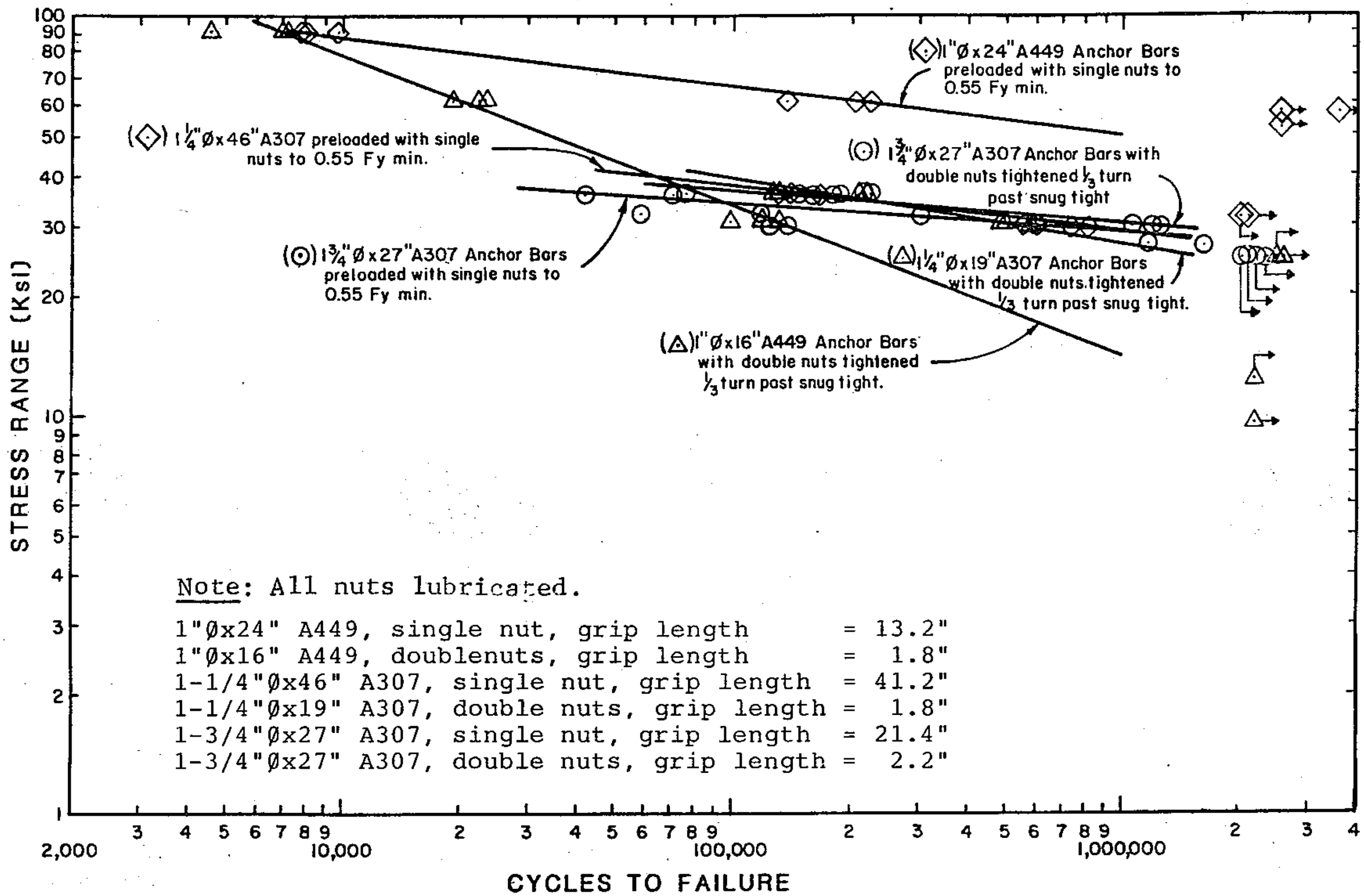

Figure B23. Comparison of fatigue lives of long anchor bars preloaded with single nuts to short anchor bars with double nuts tightened 1/3 turn past snug tight.

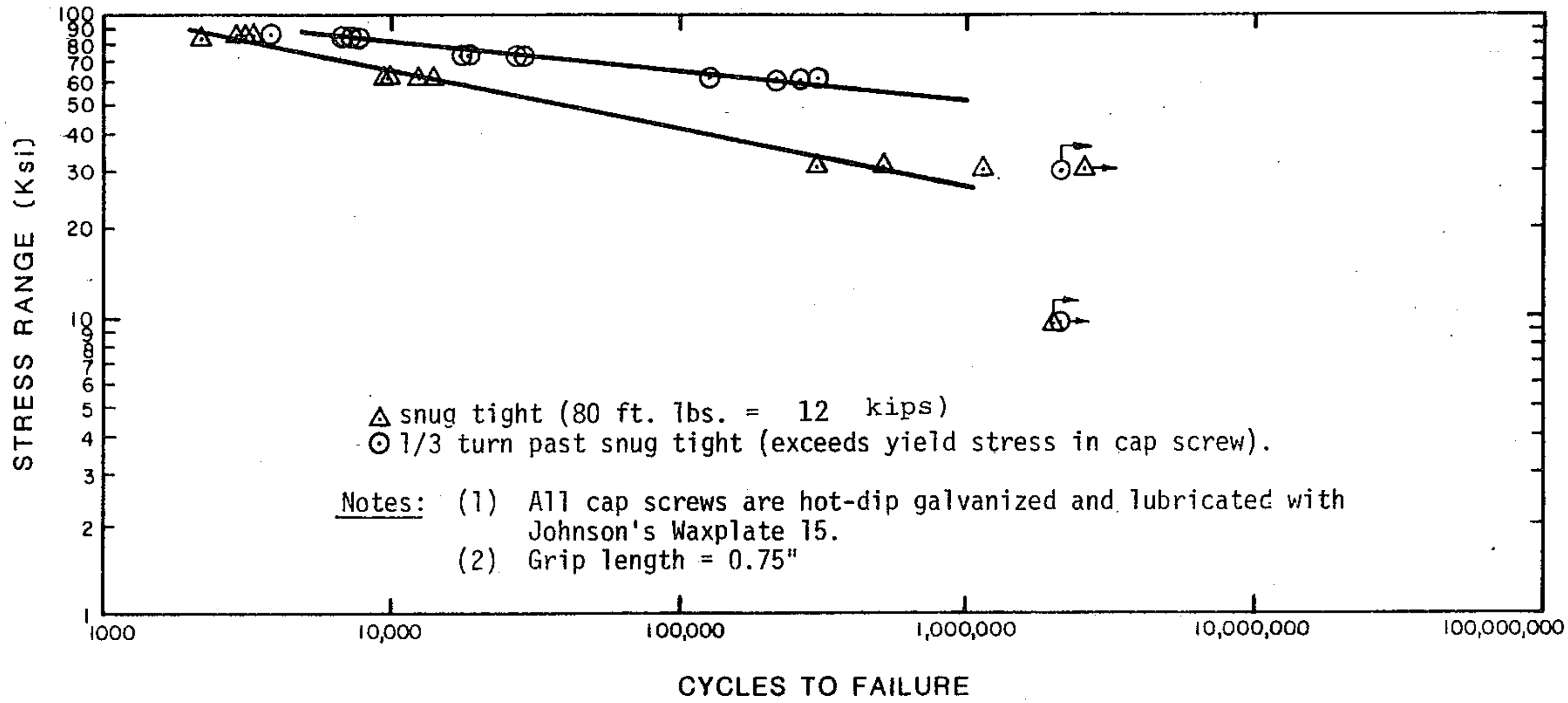

Figure C1. Effect of preloading 5/8"Ø x 1 3/4" ASTM A325 cap screws 1/3 turn past snug tight on fatigue life.

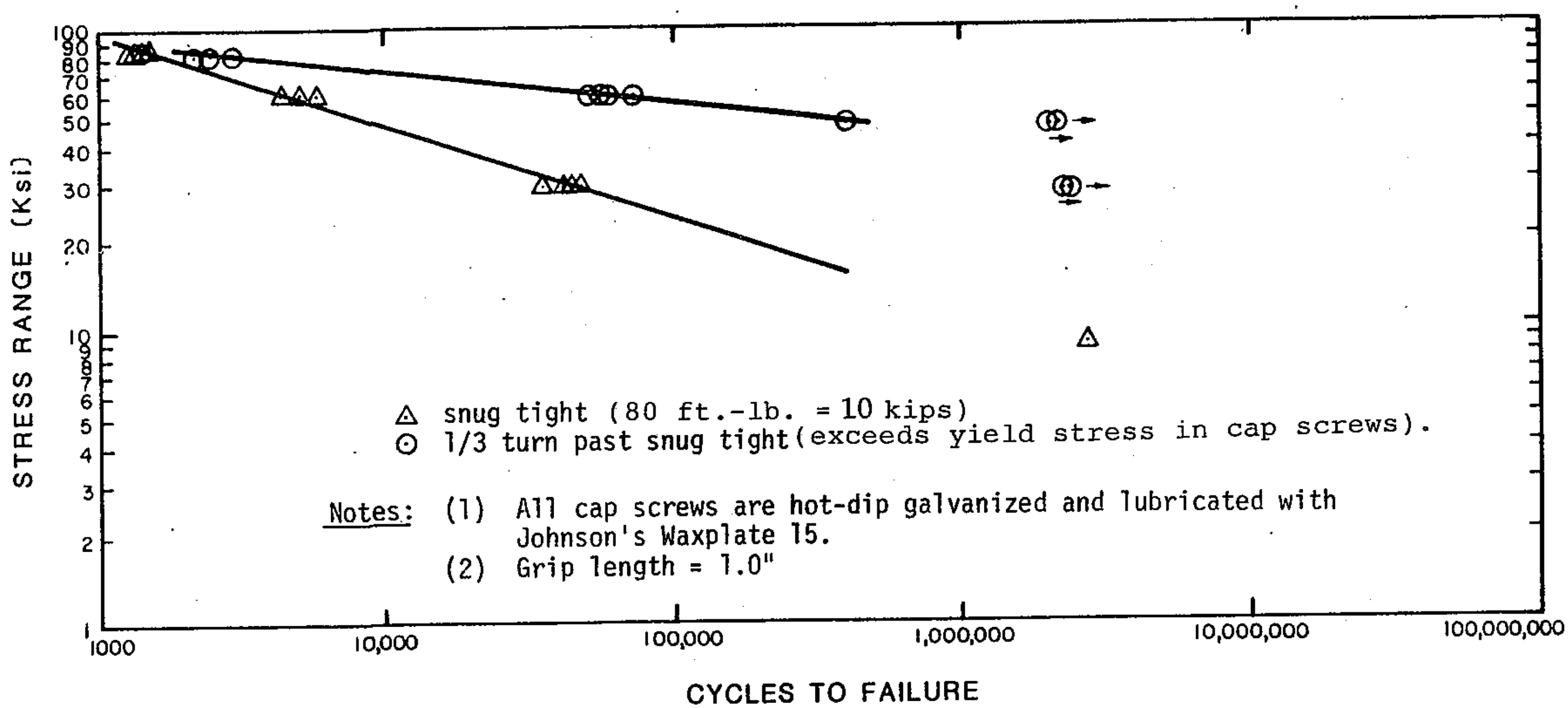

Figure C2. Effect of preloading 1"Ø x 2½" ASTM A325 cap screws 1/3 turn past snug tight on fatigue life.

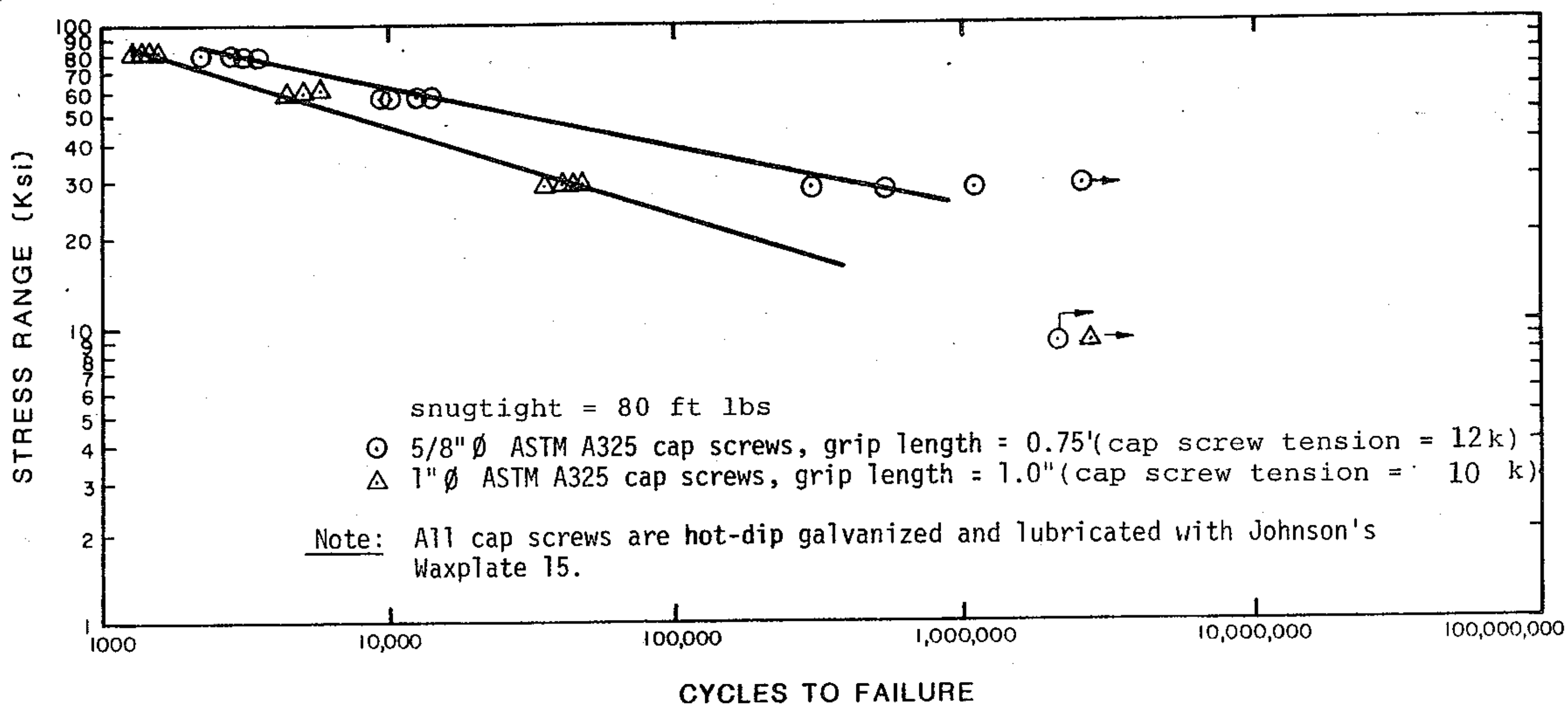

Figure C3. Effect of diameter on fatigue life of ASTM A325 cap screws tightened to snug tight only.

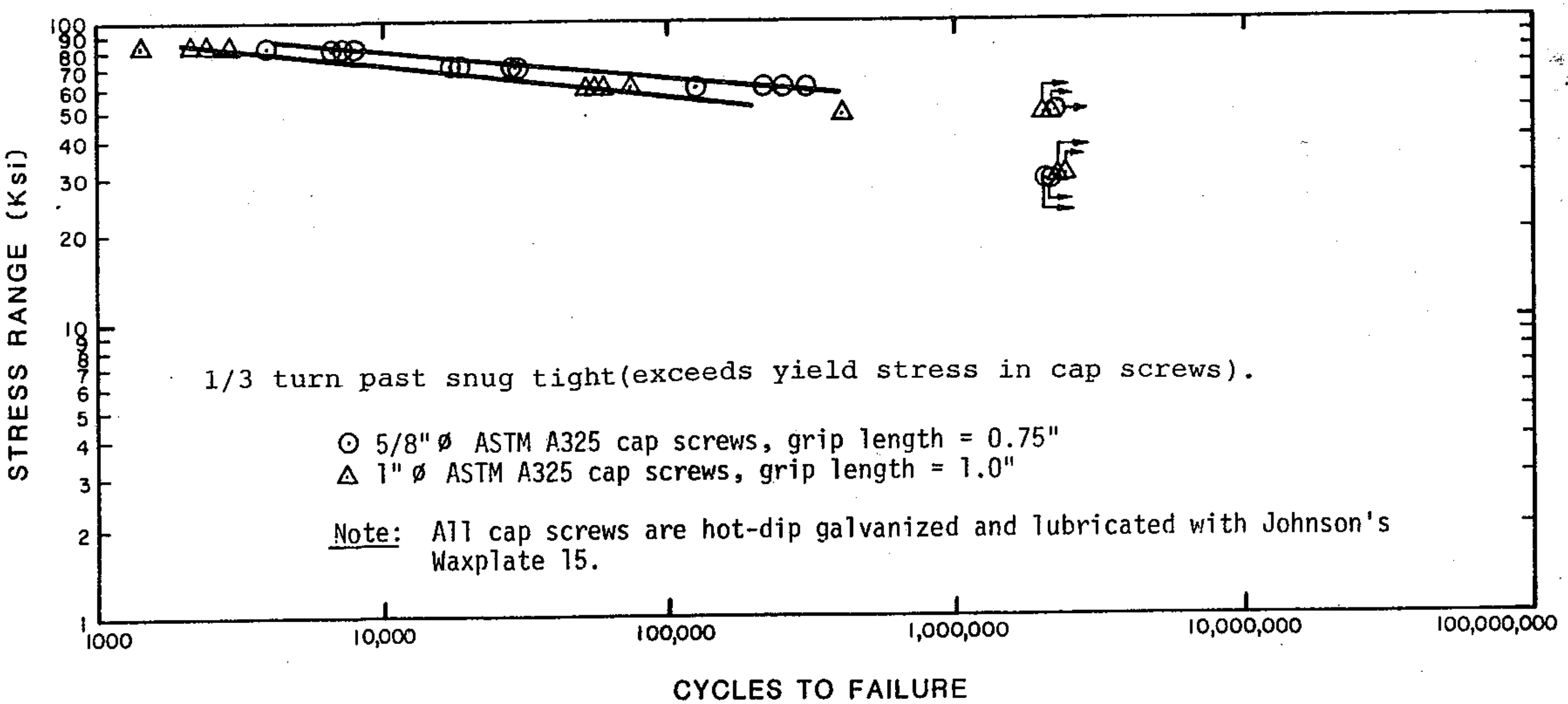

Figure C4. Effect of diameter on fatigue life of preloaded ASTM A325 cap screws tightened 1/3 turn past snug tight.

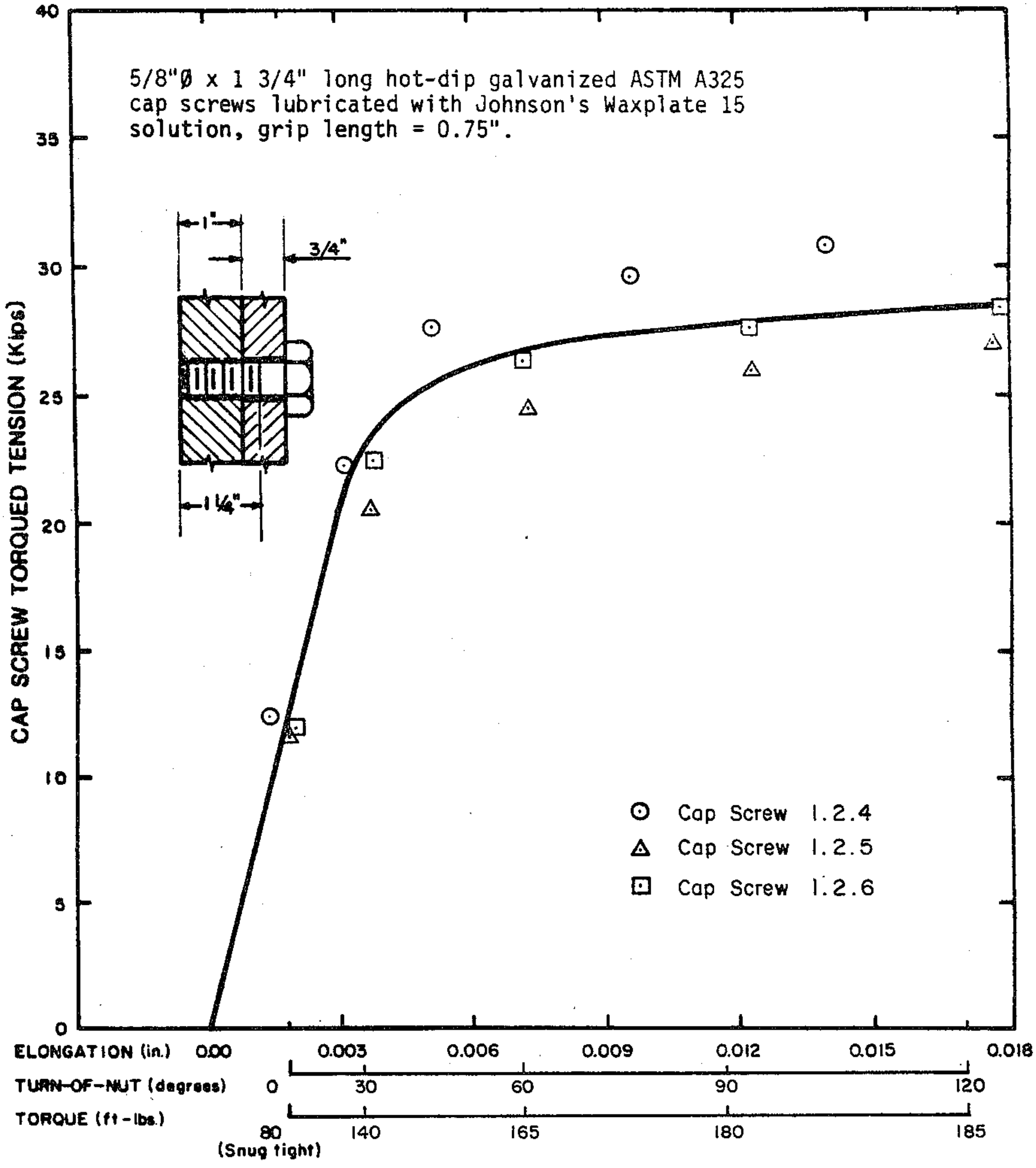

Figure D1. Relationships between torqued tension and elongation, turn-of-nut, and torque for lubricated 5/8"Ø ASTM A325 cap screws.

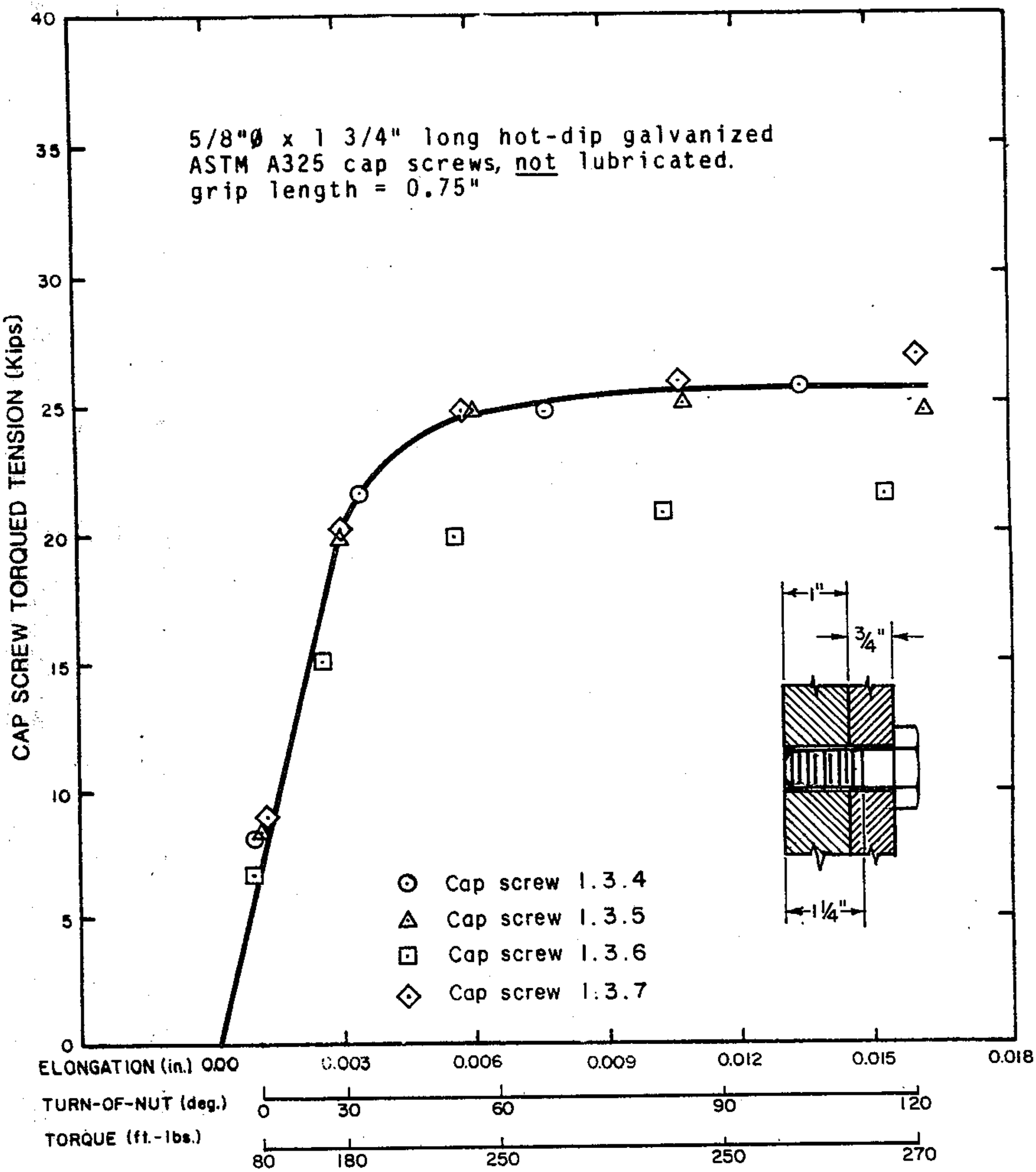

Figure D2. Relationships between torqued tension and elongation, turn-of-nut, and torque for unlubricated 5/8"Ø ASTM A325 cap screws.

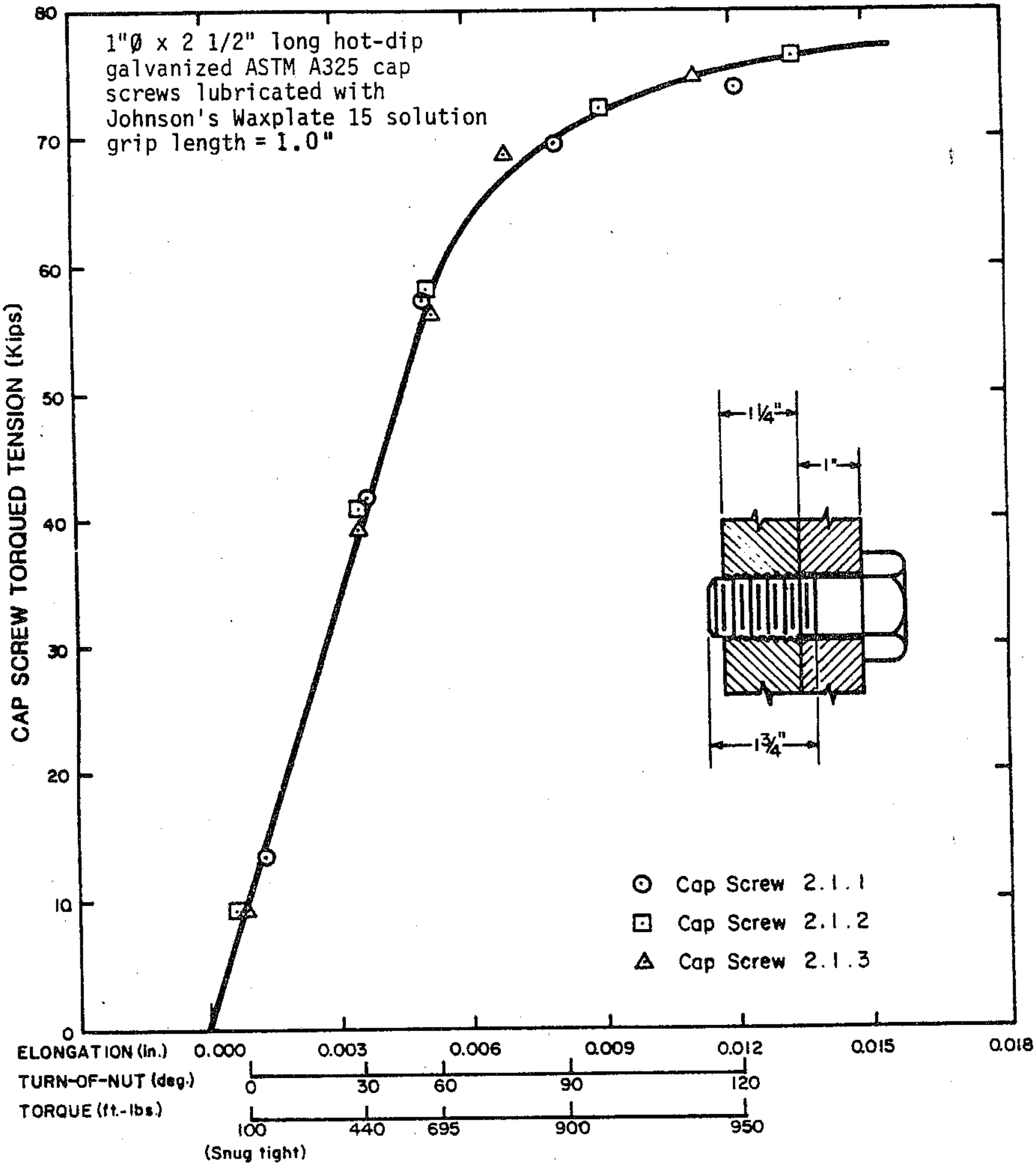

Figure D3. Relationships between torqued tension and elongation, turn-of-nut, and torque for lubricated 1"Ø ASTM A325 cap screws.

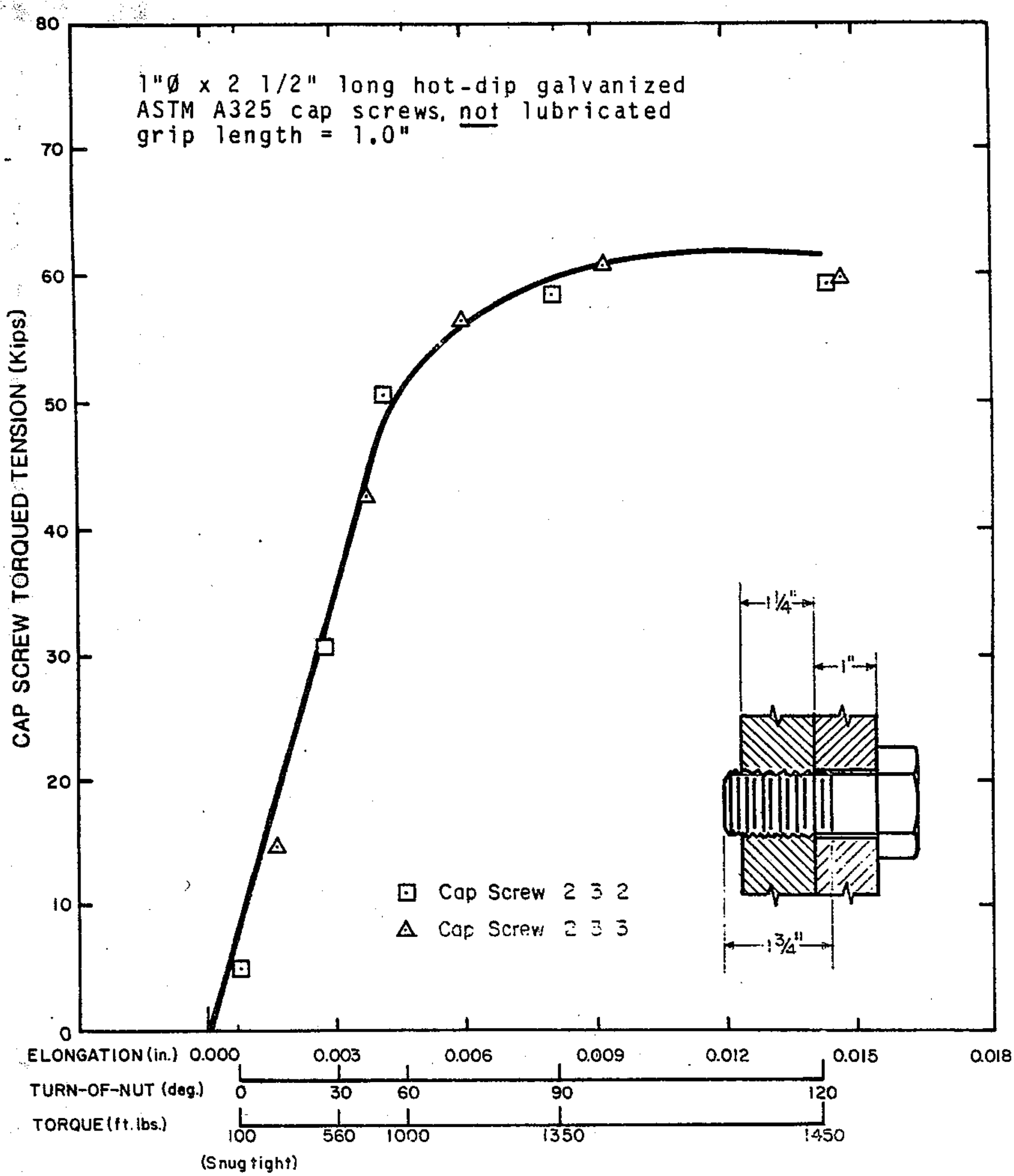

Figure D4. Relationships between torqued tension and elongation, turn-of-nut, and torque for unlubricated 1"Ø ASTM A325 cap screws.

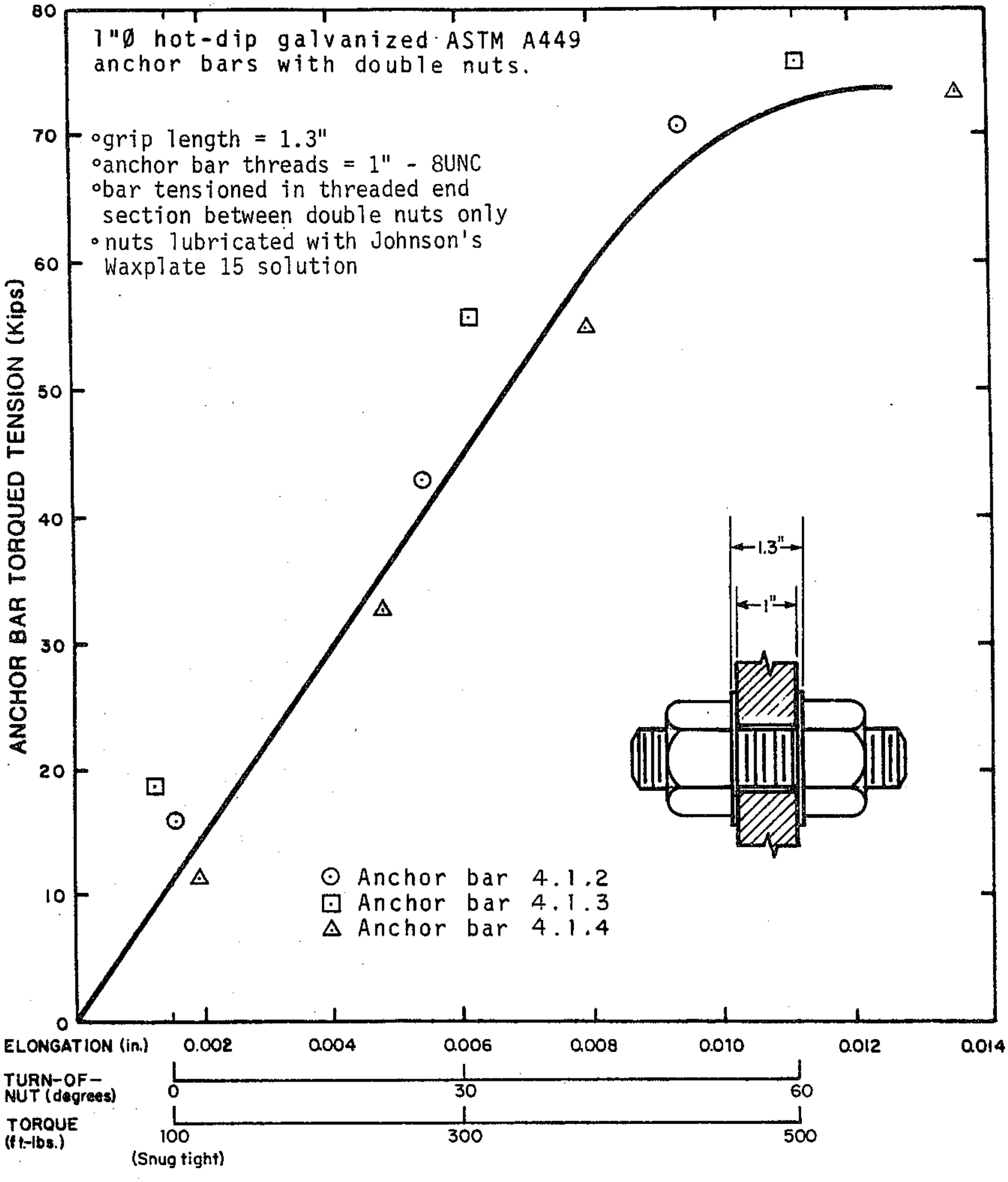

Figure D5. Relationships between torqued tension and elongation, turn-of-nut and torque for 1"Ø ASTM A449 anchor bars with lubricated double nuts.

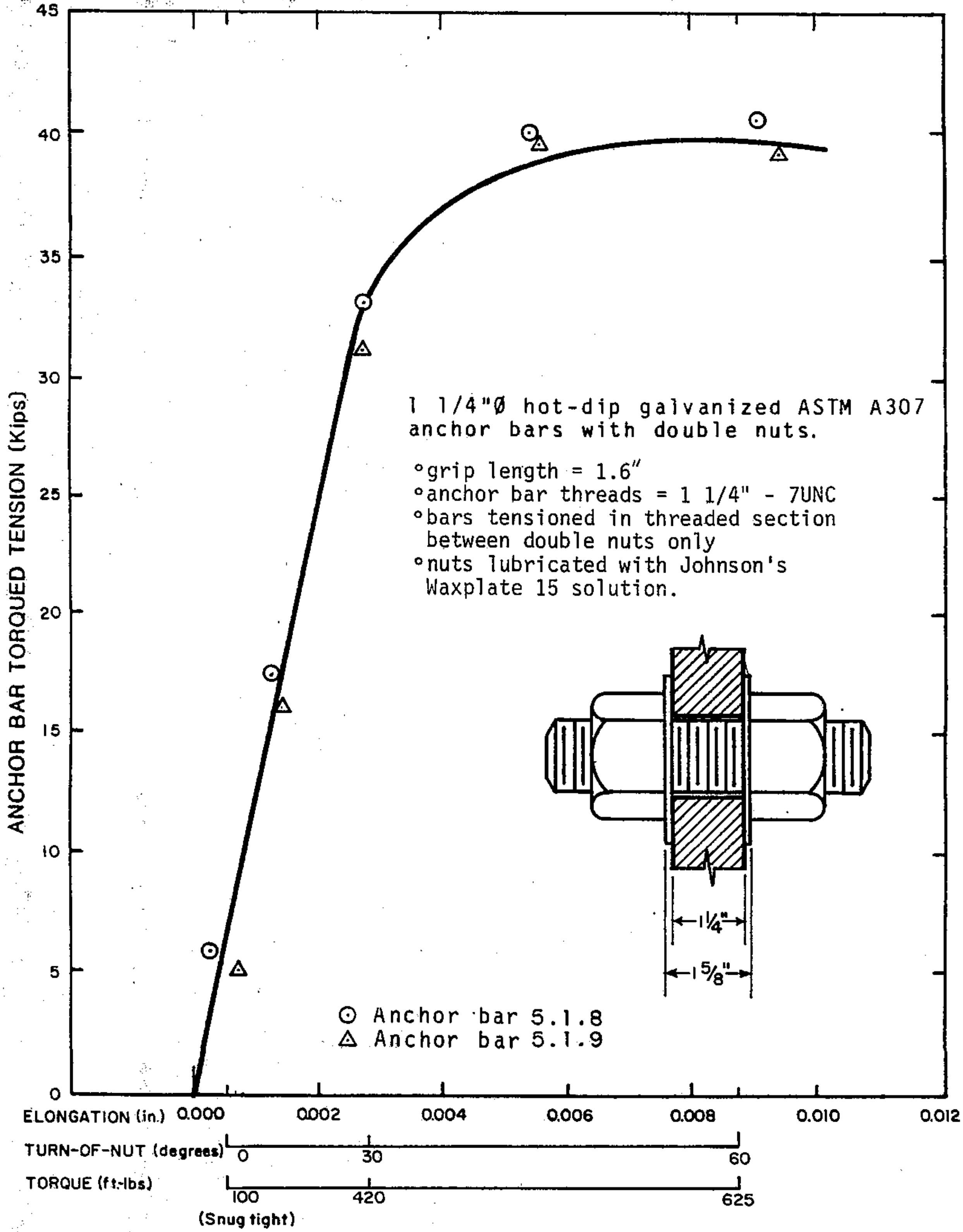

Figure D6. Relationships between torqued tension and elongation, turn-of-nut and torque for 1 1/4"Ø ASTM A307 anchor bars with lubricated double nuts

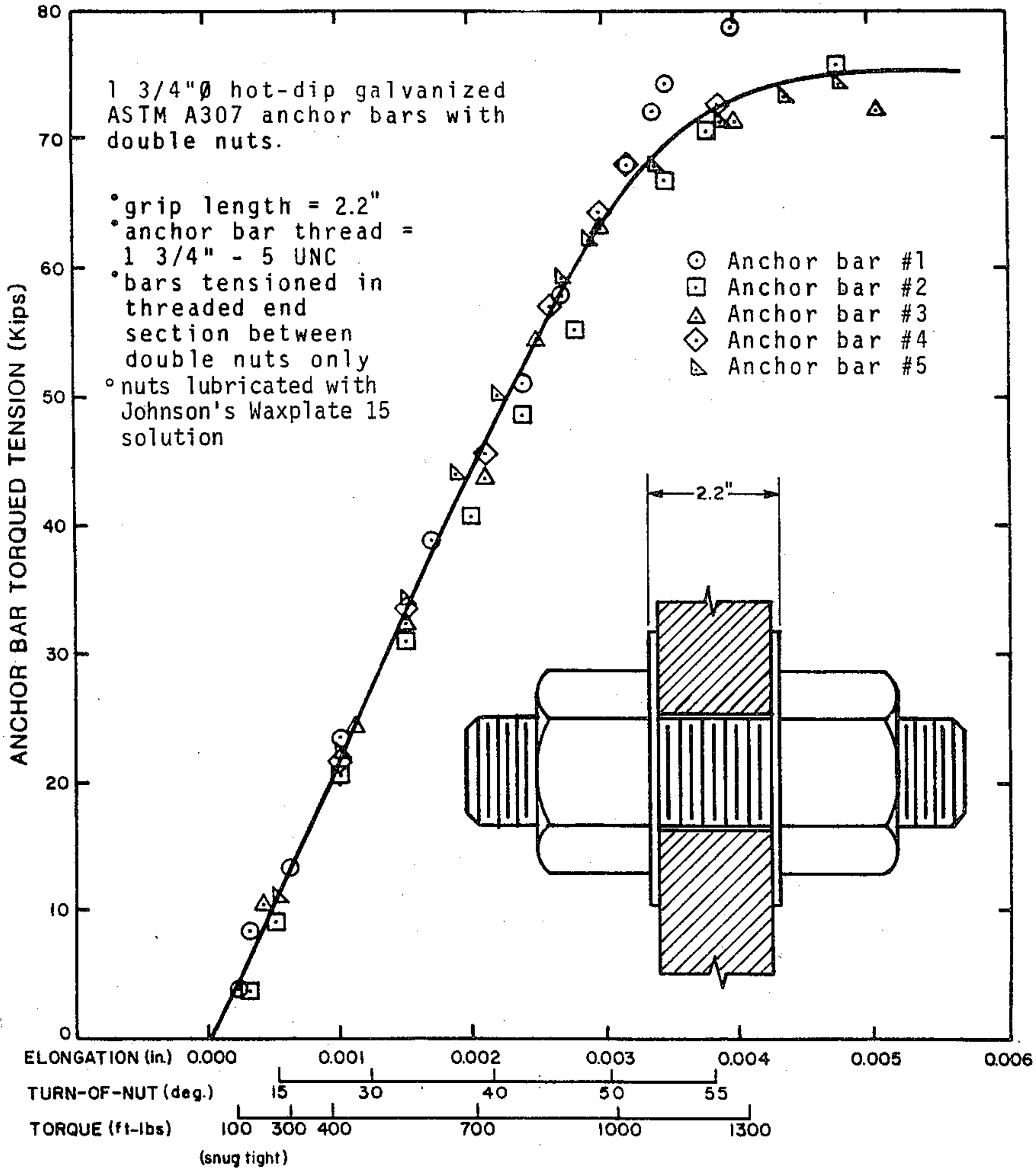

Figure D7. Relationships between torqued tension and elongation, turn-of-nut, and torque for 1 3/4"Ø ASTM A307 anchor bars with lubricated double nuts

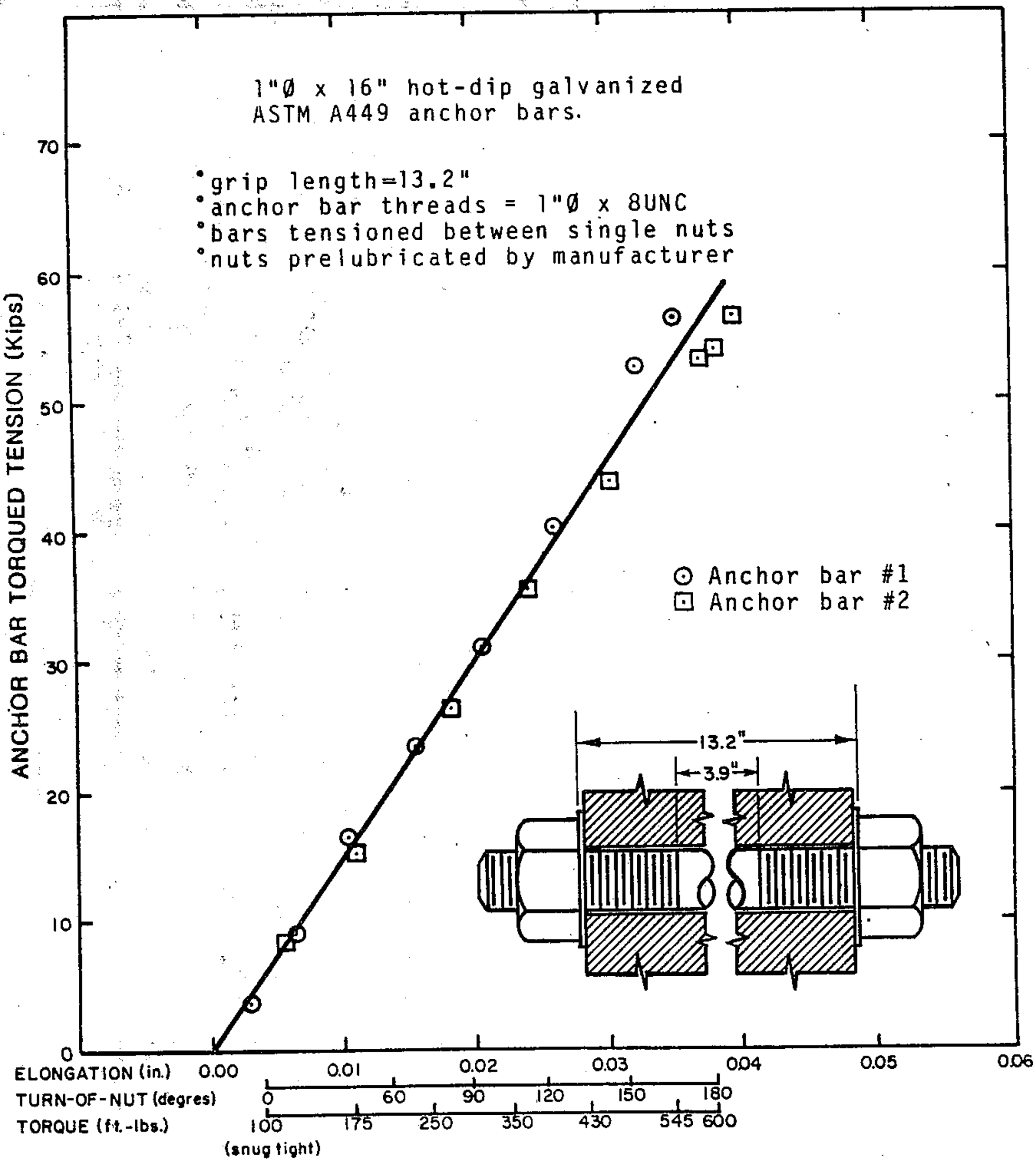

Figure D8. Relationships between torqued tension and elongation, turn-of-nut, and torque for 1"Ø x 16" ASTM A449 anchor bars with lubricated single nuts

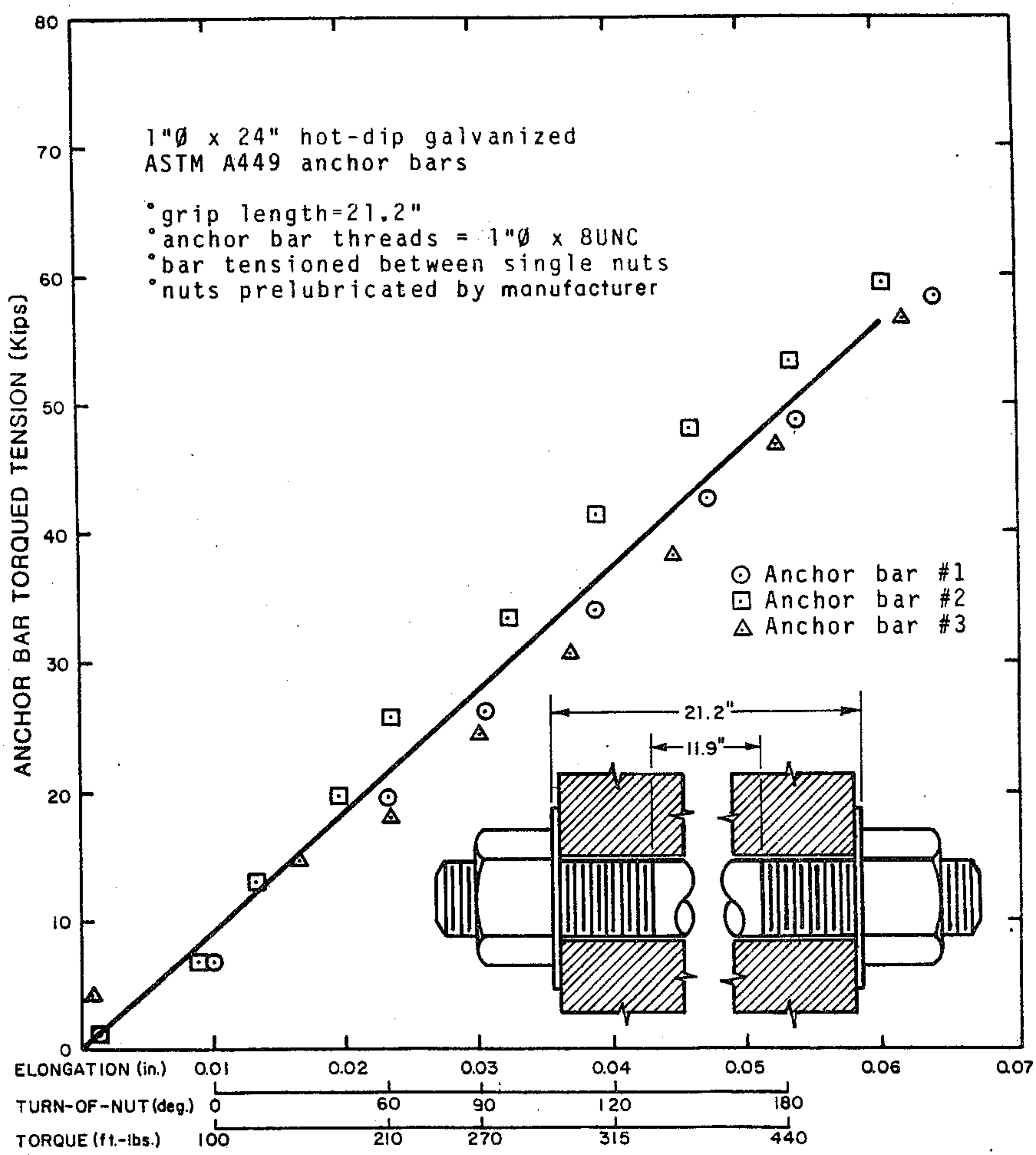

Figure D9. Relationships between torqued tension and elongation, turn-of-nut, and torque for 1"Ø x 24" ASTM A449 anchor bars with lubricated single nuts

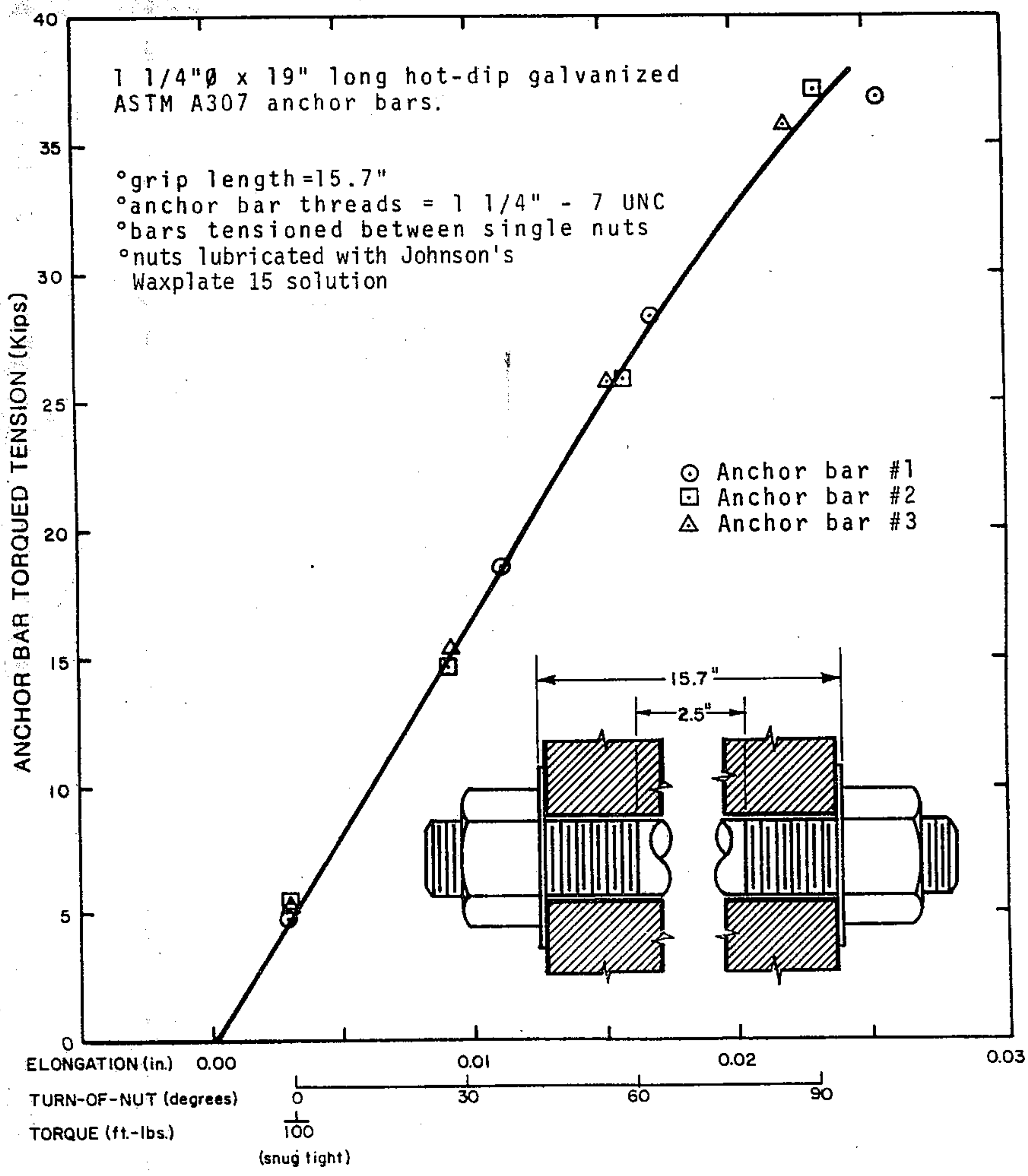

Figure D10. Relationships between torqued tension and elongation and turn-of-nut for 1 1/4"Ø x 19" ASTM A307 anchor bars with lubricated single nuts

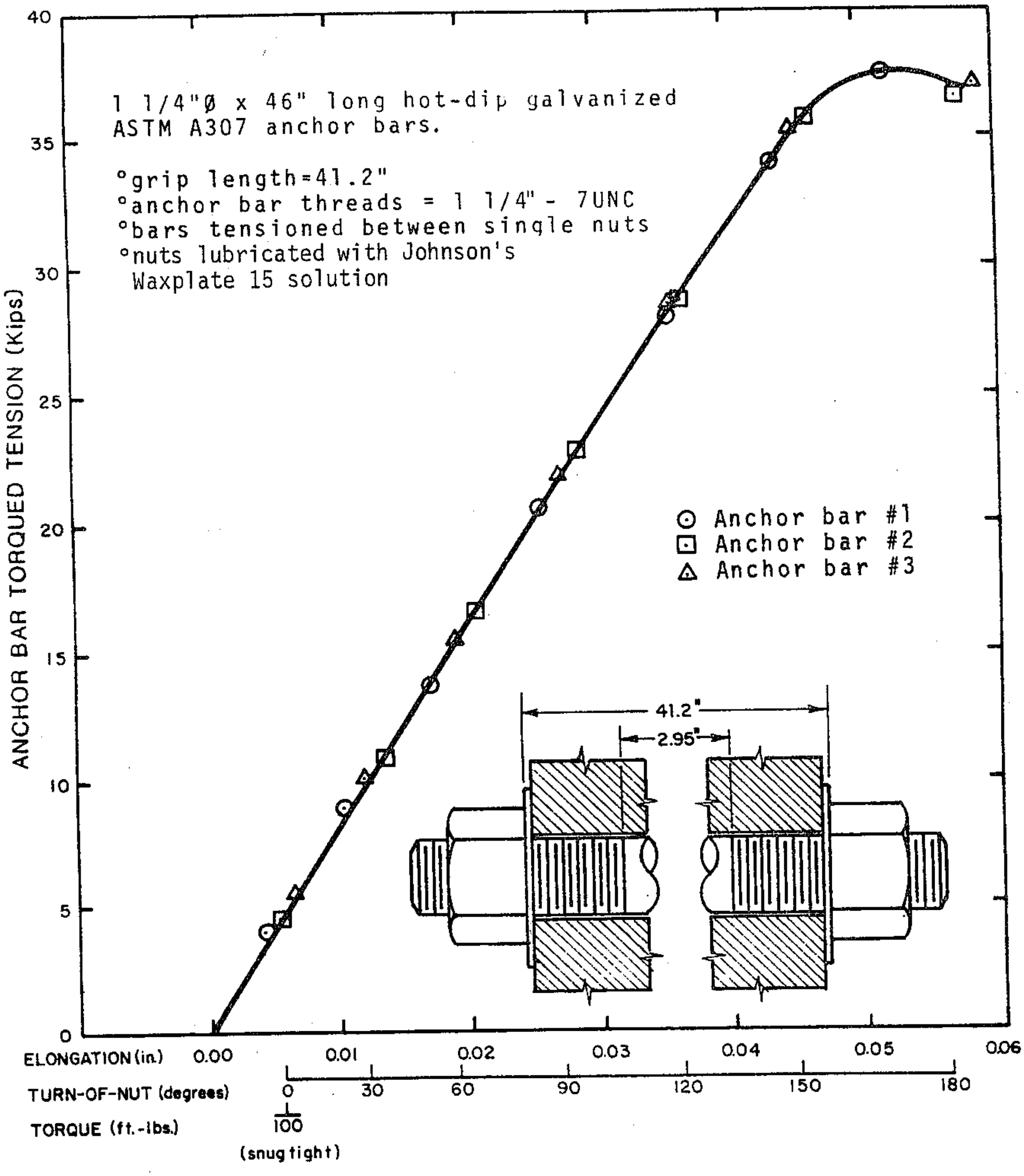

Figure D11. Relationships between torqued tension and elongation and turn-of-nut for 1 1/4"Ø x 46" ASTM A307 anchor bars with lubricated single nuts

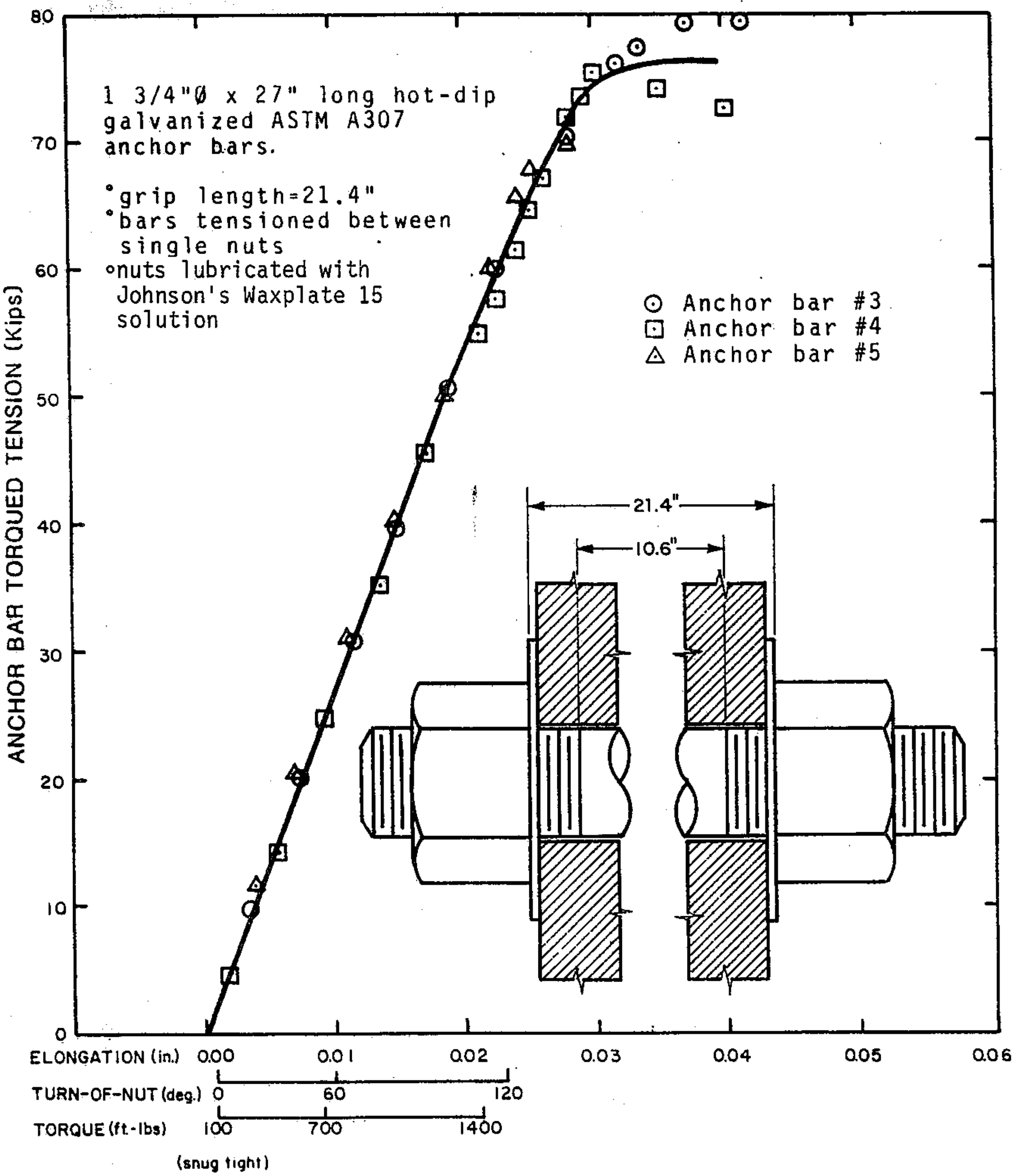

Figure D12. Relationships between torqued tension and elongations, turn-of-nut, and torque for 1 3/4"Ø x 27" ASTM A307 anchor bars with lubricated single nuts

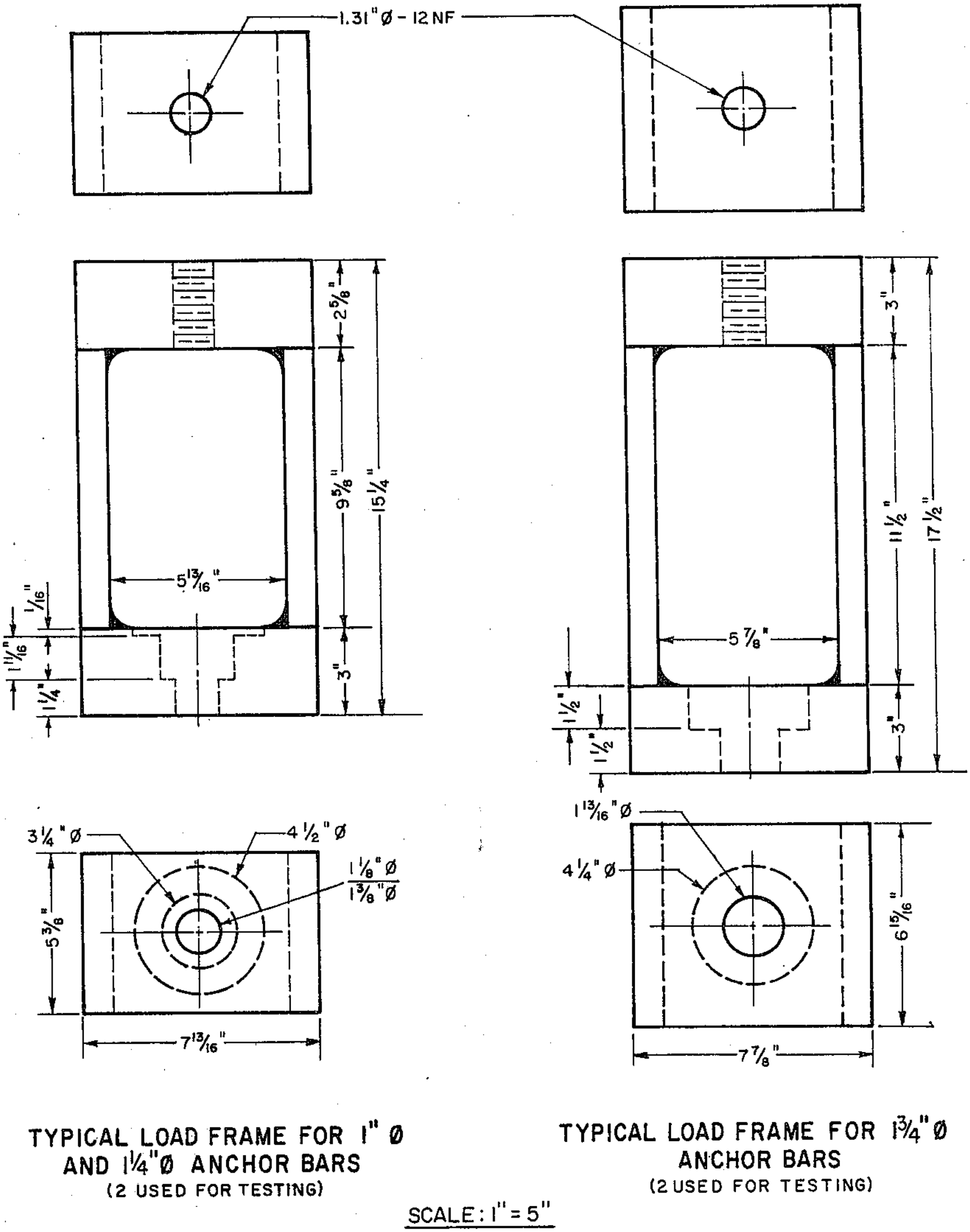

Figure E1. Load frames for cyclic testing anchor bars.

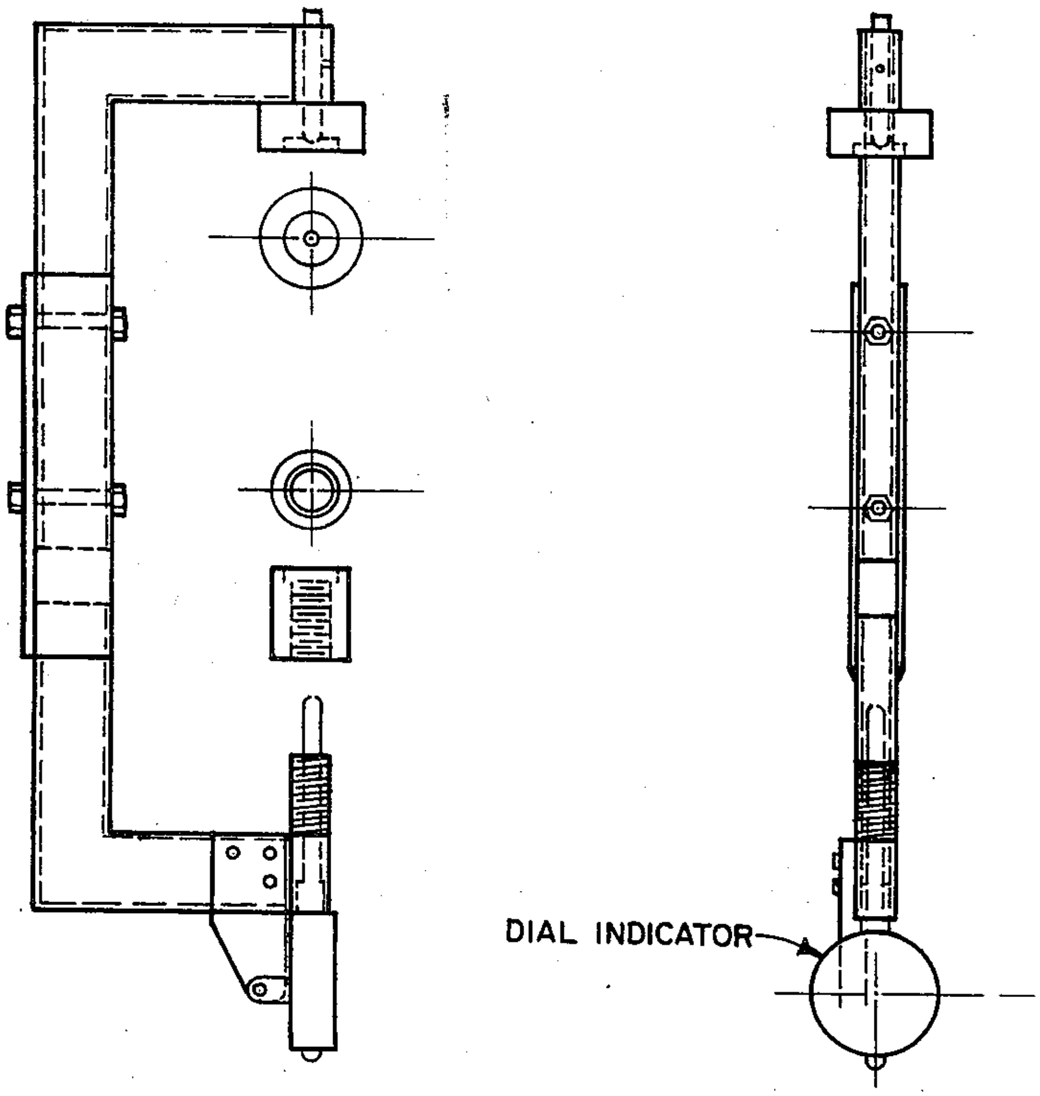

Figure E2. Tubular steel "C" frame used to measure elongation of anchor bars.

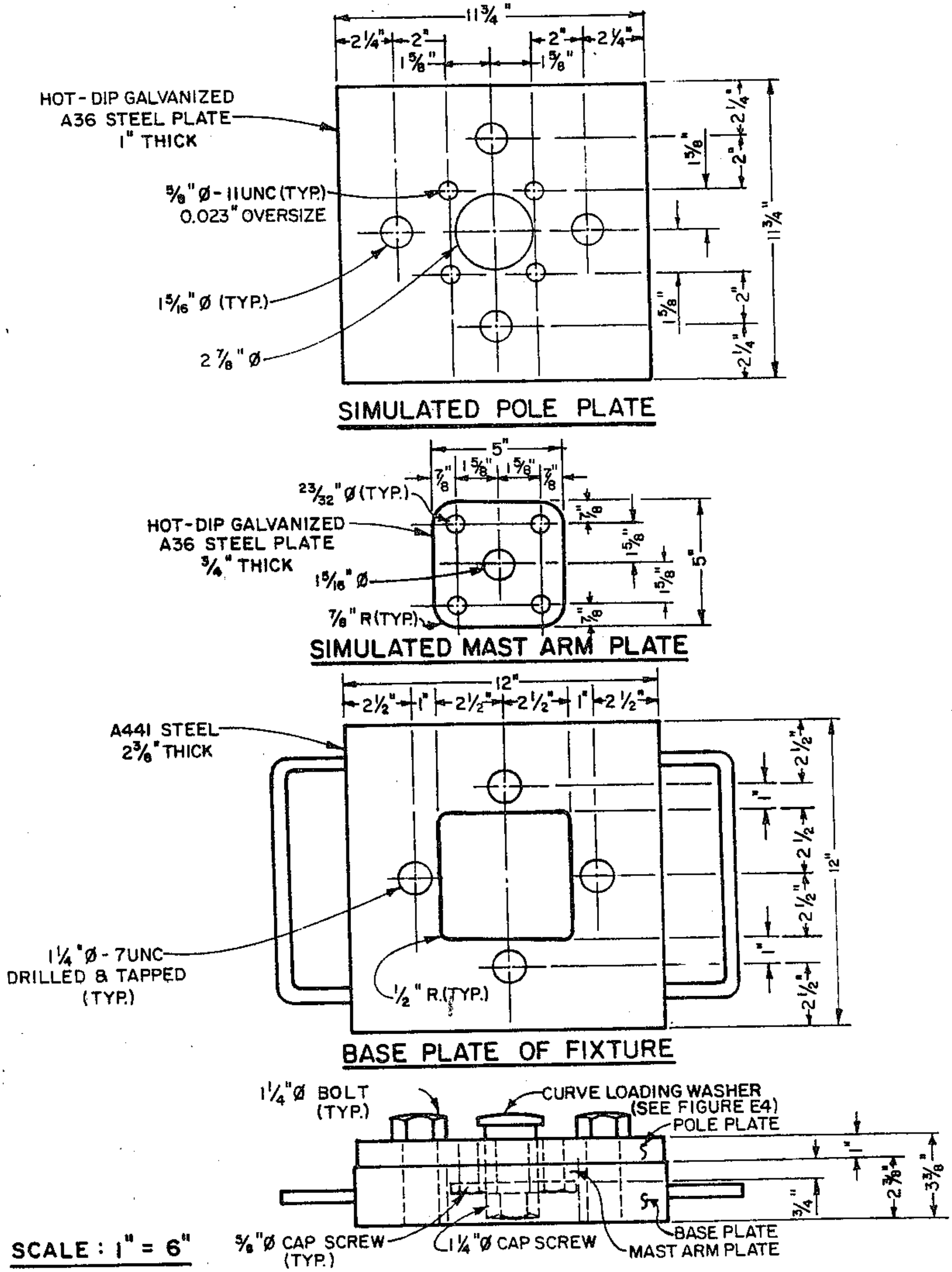

Figure E3. Test fixture for 5/8" Ø x 1 3/4" ASTM A325 hot-dip galvanized cap screws.

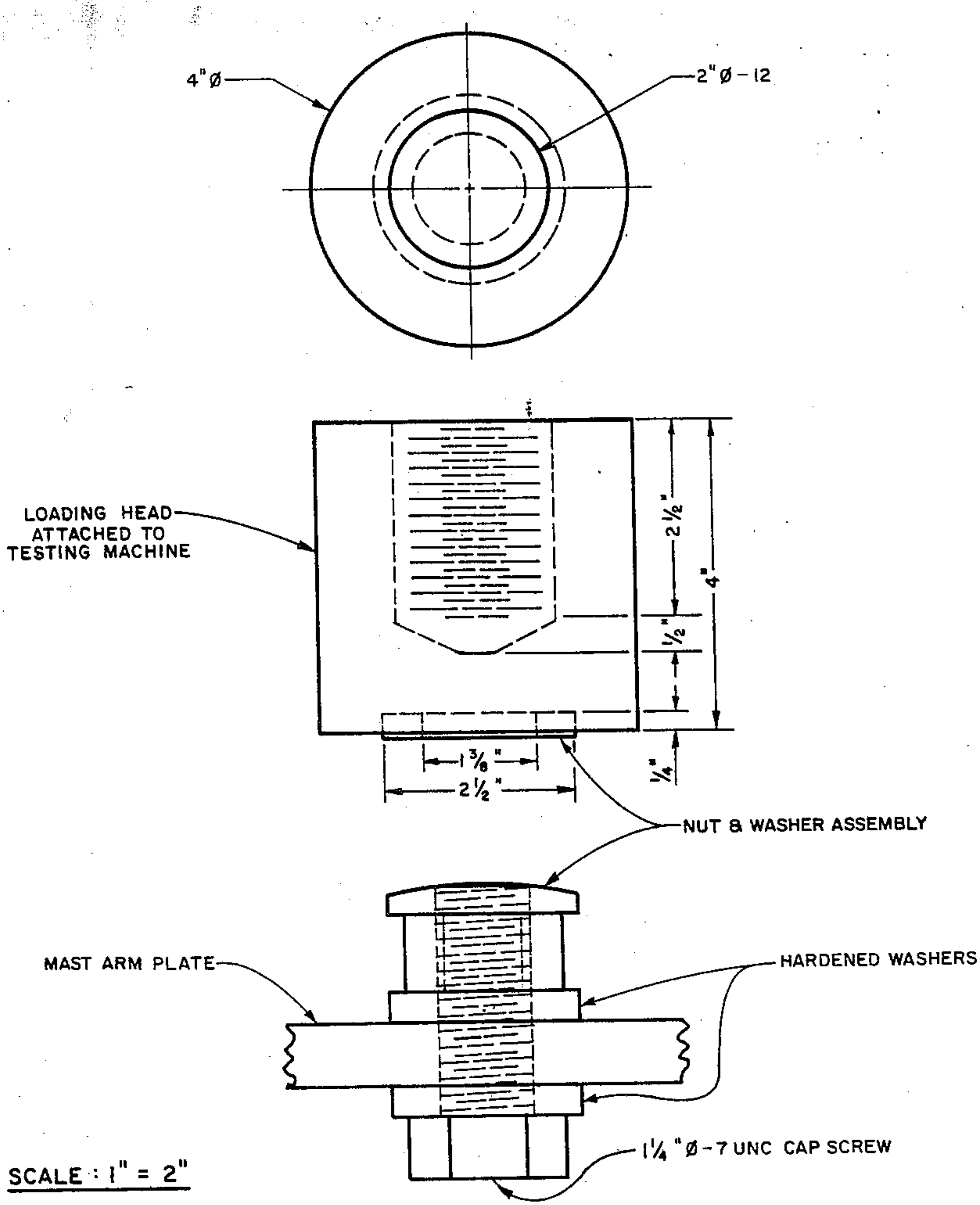

Figure E4. Loading head fixture with curved washers for testing 5/8" Ø ASTM A325 hot-dip galvanized cap screws.

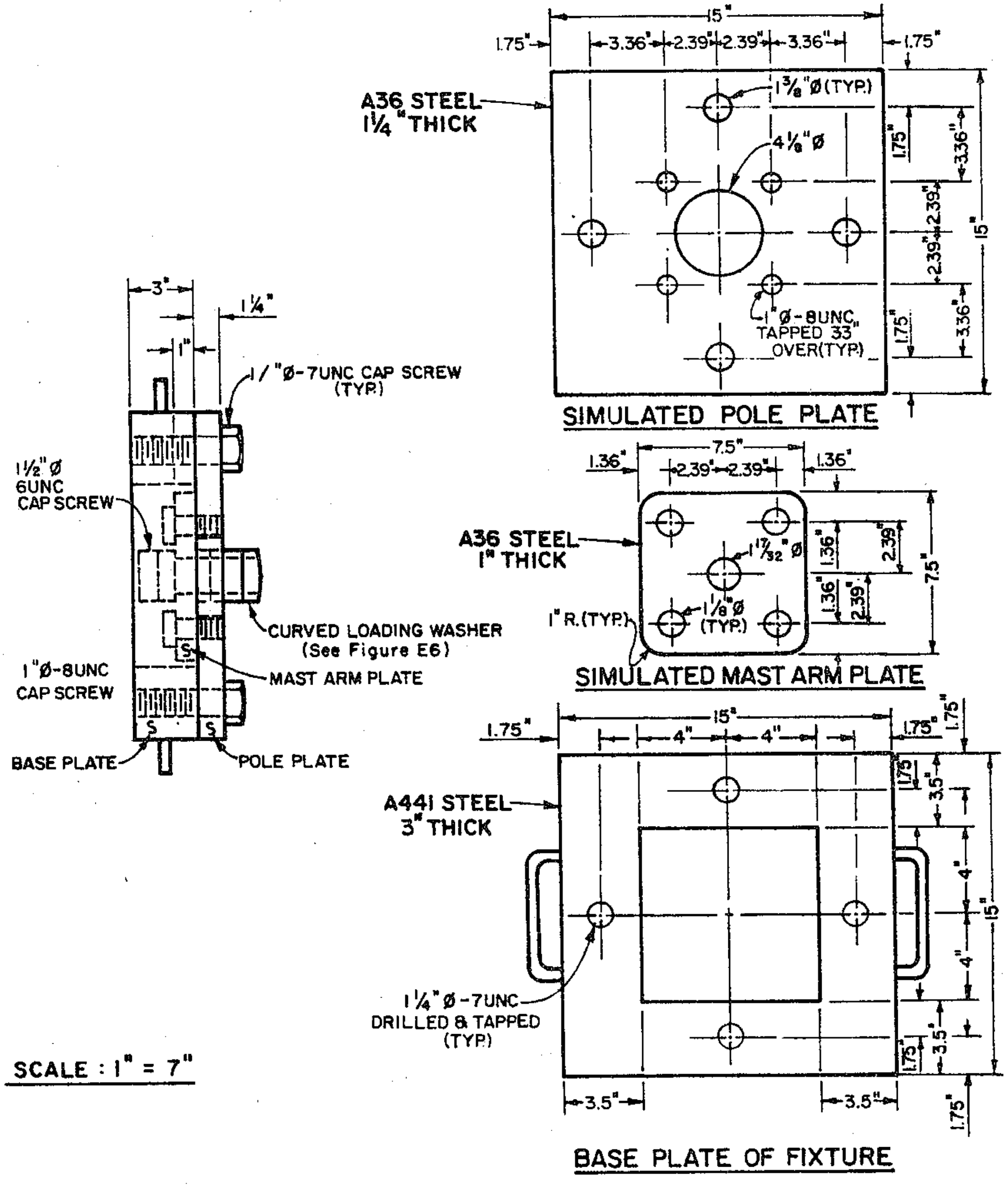

Figure E5. Test fixture for 1" Ø x 2" ASTM A325 hot-dip galvanized cap screws.

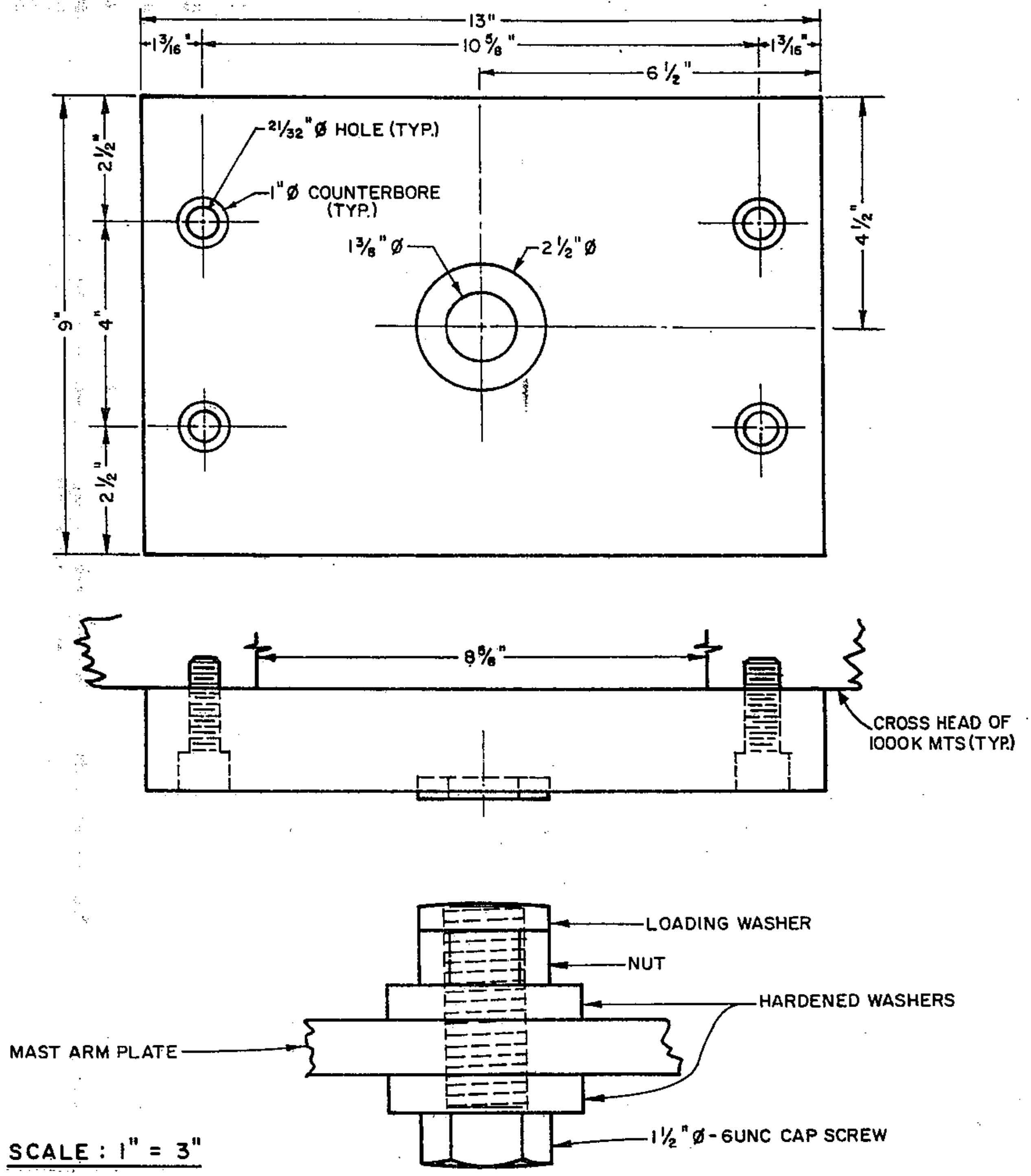

Figure E6. Loading head fixture with curved washer for testing 1" Ø ASTM A325 hot-dip galvanized cap screws.

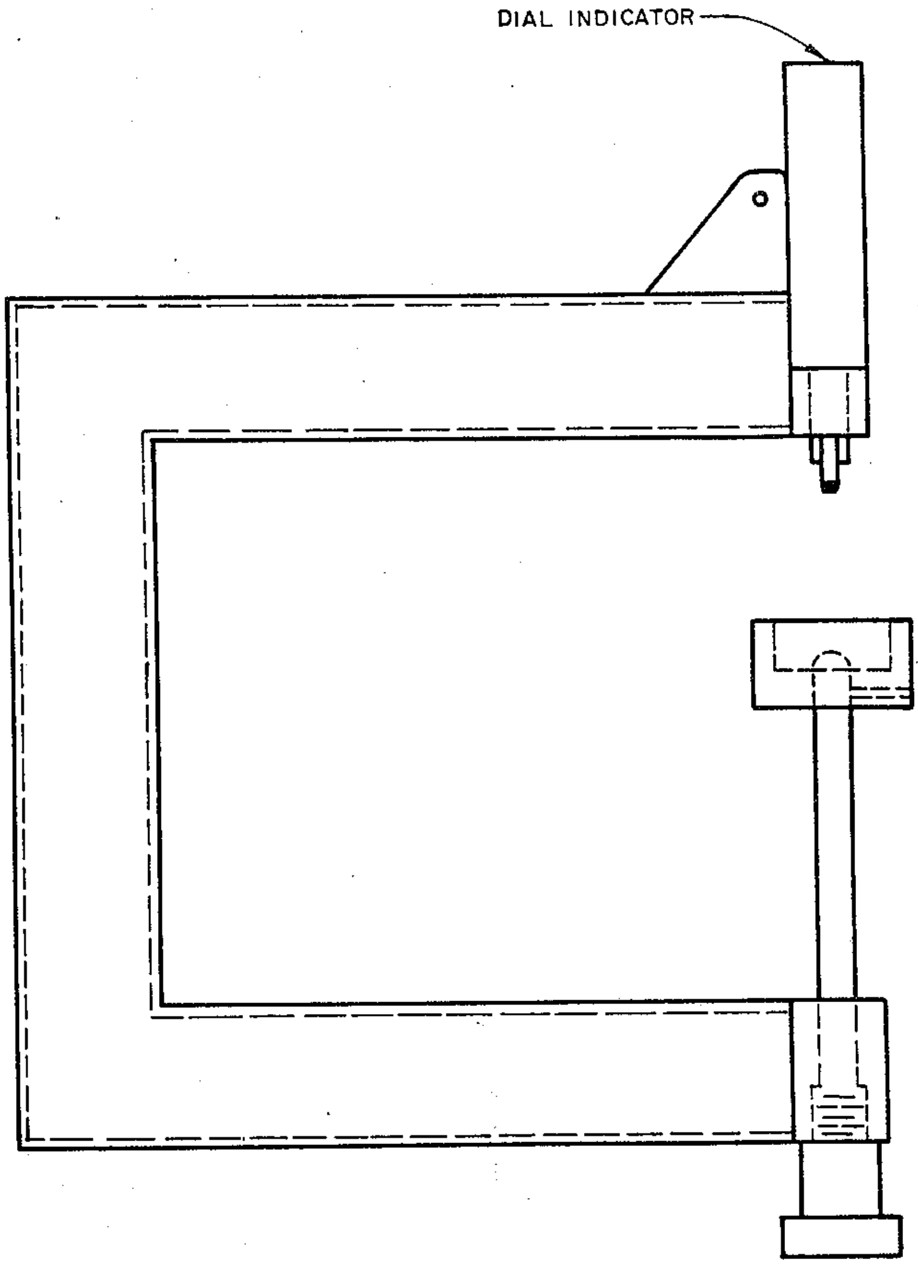

Figure E7. Tubular steel "C" frame used to measure elongation of cap screws.