THE EFFECT OF BURRS ON SHEAR CAPACITY OF BOLTED CONNECTIONS

key words –
1 - bolted conn's
2 - high-strength bolts
3 - slip resistance, joints

Final Report

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June 20, 1991

Mr. Nestor Iwankiw
American Institute of Steel Construction
One East Wacker Drive, Suite 3100
Chicago, IL 60601-2001

Dear Nestor:

Enclosed is a research report entitled "The Effect of Burrs on Shear Capacity of Bolted Connections." If additional information is needed, please contact me at the address shown above or by phone at 405/744-5257.

I enjoyed working on this project and I hope the results are useful to you. If you are in need of research assistance in the future, do not hesitate to contact me.

Sincerely,

Farrel Zwerneman
Associate Professor

cf

Enclosure

ABSTRACT

An experimental research program was conducted to assess the effect of burrs on the shear capacity of bolted connections. Both slip-critical and bearing connections were included in the study. Burr heights ranged from 0 in. to 0.215 in. The study concentrated on single-bolt connections utilizing 3/4-in. diameter A325 bolts, but one small group of specimens was constructed with multiple bolts and another small group was constructed with 1-in. diameter A490 bolts. Methods of bolt tightening included turn-of-nut, calibrated wrench, tension control wrench, and direct tension indicator.

Based on the test results, it is concluded that burrs extending 1/16 in. or less above the plate surface are not detrimental to the strength of bearing connections. This same burr height is also permissible in slip-critical connections, *if proper bolt tension is achieved.* Proper bolt tension can be achieved in single bolt connections using tension control wrench or direct tension indicator methods; proper tension cannot be reliably achieved using turn-of-nut or calibrated wrench methods. In multiple bolt connections, tensions in the first bolts tightened were significantly lower than required. These low tensions occurred regardless of the tightening method used. Further research is needed with multiple bolt connections.

ACKNOWLEDGMENTS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

This research was conducted to assess the effect of burrs on the shear capacity of bolted connections. All burrs were formed as a by-product of the hole punching operation. An example of the type of burr under investigation can be seen in Figure 1. The burr seen in Figure 1 is approximately 0.10 in. in height; in this study, burrs ranged in height from 0 to 0.215 in.

The presence of a burr extending above the surface of a plate will interfere with contact between faying surfaces. This interference may be assumed to have two detrimental effects: (1) the reduction in contact area may reduce the friction capacity of slip critical connections, and (2) the increase in grip may increase bending stresses in the bolt, resulting in premature shear failure. Lacking evidence to refute these two assumptions, members of the Research Council on Structural Connections (RCSC) have taken a conservative approach in their "Specification for Structural Joints Using ASTM A325 or A490 Bolts" [11] (subsequently referred to as the RCSC Specification) in regard to the presence of burrs. Section 3(b) of this Specification requires "Burrs that would prevent solid seating of the connected parts in the snug tight condition shall be removed" and Section 8(c) states "the snug condition is defined as the tightness that exists when all plies in a joint are in firm contact." The effect of these requirements has been slightly mitigated by statements in the Commentary: "Based upon tests which demonstrate that the slip resistance of joints was unchanged or slightly improved by the presence of burrs, burrs which do not prevent solid seating of the connected parts in the snug tight condition need not be removed," and "in some joints, it may not be possible at snug tight to have contact throughout the faying surface area."

If the above quotations are viewed from a common sense point of view, compliance with the Specification would not result in a significant manpower requirement for fabricators using qualified personnel and well maintained equipment. If equipment is in good working

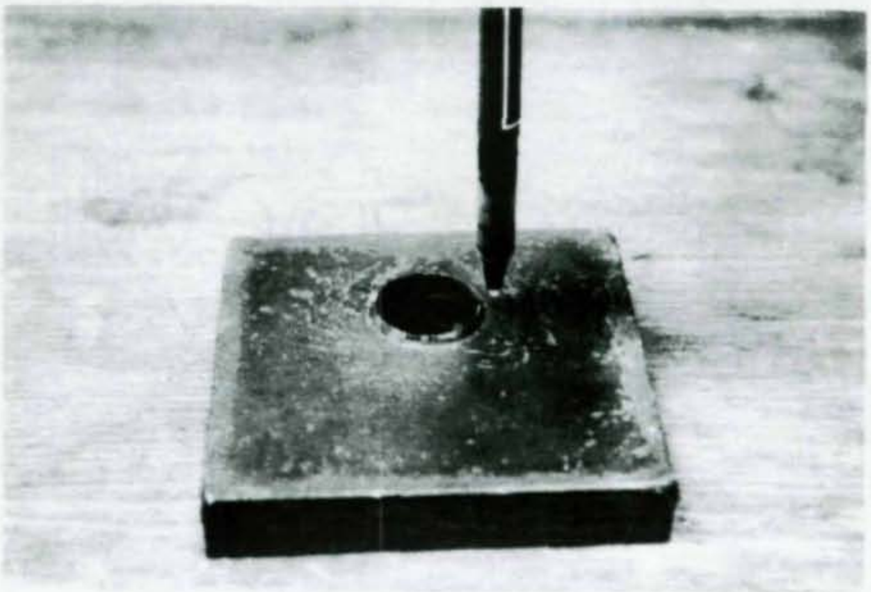

Figure 1. Punched Hole Surrounded by Large Burr

order and is properly operated, burr heights typically fall in the 1/64- to 1/32-in. range. Common sense dictates that a burr of this size is not a threat to connection strength. Surface grinding should be required only if burrs cause an observable seating problem.

If, however, the above quotations are viewed from a strict legalistic point of view, the extension of any material above the plate surface will interfere with "solid seating." Interference exists even if it cannot be seen. This legalistic interpretation has been applied in many cases and effectively results in the requirement that surface grinding take place around every punched hole. Thousands of manhours are spent each year performing what is most often an unnecessary operation.

1.2 Objectives

The objective of this research is to determine if the presence of burrs extending above faying surfaces in bolted connections adversely effects the load-carrying capacity of these connections. If the presence of burrs is found not to be detrimental in terms of connection strength, modifications to Sections 3(b) and 8(c) of the RCSC Specification will be proposed.

1.3 Scope

This research program involved the construction and testing of 430 bolted connections: 385 of these connections were friction-type and 45 were bearing-type; 167 of these connections were constructed specifically to measure the effect of the burrs on bolt tension and the remainder were constructed to measure the effect of burrs on connection shear capacity; 422 of the connections were constructed with 3/4-in. diameter A325 bolts and 8 of the friction connections were constructed with 1-in. diameter A490 bolts; 400 of the connections were single-bolt connections and 30 of the friction connections constructed with 3/4-in. bolts were four-bolt connections. Burr heights ranged from a minimum of 0 in. to a maximum of 0.215 in. Methods of obtaining required tension for friction connections included turn-of-nut, calibrated wrench, tension control, and direct tension indicator tightening. All specimens were made from A572 Grade 50 steel plate.

CHAPTER 2

PREVIOUS WORK

2.1 Bearing Connections

The shear capacity for high strength bolts specified by the American Institute of Steel Construction (AISC) [2] is based largely on the work of Wallaert and Fisher [19] and Rumpf and Fisher [12]. References [12] and [19] form the basis for design recommendations in *Guide to Design Criteria for Bolted and Riveted Joints* [7] (subsequently referred to as the Guide) which, in turn, forms the basis for the AISC criteria. Extensive research has also been conducted by Chesson, Faustino, and Munse [4].

In Reference [19] the shear strength of A325 bolts was reported to be approximately 80 ksi and the ultimate tensile strength was reported to be approximately 120 ksi. This same 120-ksi ultimate tensile strength is currently the minimum ultimate tensile strength permitted in ASTM A325-89 for bolts 1 in. in diameter or less. In Reference [7] it is shown that the shear strength of a high-strength bolt is equal to slightly more than 60% of the ultimate tensile strength of that bolt. Sixty percent of 120 ksi is 72 ksi, which is the AISC nominal strength for A325 bolts with threads excluded from the shear plane. Since the shear strength of a high-strength bolt is slightly more than 60% of the ultimate tensile strength of the bolt, and the ultimate tensile strength is generally greater than the 120-ksi minimum [7], it is expected that experimentally determined shear strengths will exceed 72 ksi.

References [4] and [15] include studies of the effect of grip size on bolt shear capacity. Both of these studies conclude that increasing the grip causes an increase in bolt shear strength, but Reference [15] states the increase is not of major consequence. In both studies it is hypothesized that the increase in capacity is the result of increased bending in the bolt which leads to a larger projected area in the shear plane. The current tests are also expected to increase bending in the bolt, but the conditions are not exactly the same as the referenced studies. In the current tests any increase in grip size will be the result of gaps between plates so that bearing on bolts will not be continuous.

The results of tests more similar to the current work have been reported by Yura, Hansen, and Frank [21]. In these tests, undeveloped fillers were placed between main plates and splice plates. Bolts were fully tensioned and slip coefficients as well as ultimate shear strengths were reported. Specimens with fillers 1/4 in. thick achieved 98.8% of the shear capacity achieved by specimens with no fillers. Capacity dropped to approximately 87% when 3/4-in. fillers were used. Since burrs in the present tests are well under 1/4 in. in height, the work of Yura, Hansen, and Frank suggests the burrs may not be detrimental.

2.2 Friction Connections

To assess the effect of burrs on the slip capacity of a bolted joint, their effect on both bolt tension and slip coefficient must be examined. Even if the slip coefficient is unaffected by the presence of burrs, the slip capacity in terms of force can be adversely affected by low bolt tension.

Much of the past work related to bolt tension has been directed toward turn-of-nut tightening. Reference [14] states that the rotation-tension relationship depends on stiffness inside the grip, which depends on the number, thickness, and flatness of plies. Several independent studies provide data to support this statement. Reference [5] reported that bolts installed in a calibrator required more rotation to reach a certain tension than did bolts installed in steel plates, because the calibrator was less stiff than the steel plates. Reference [1] concluded that bolts installed in oversize holes carried less tension than bolts installed in standard holes because higher pressures under the head and nut caused these plates to compress more in the vicinity of the holes. In Reference [10], Polyzois and Yura found that more nut rotation was necessary to tension bolts when burrs were present in the connection.

Other methods for tensioning bolts are commonly used, but have not been studied as extensively as turn-of-nut. The ability of direct tension indicators to accurately measure bolt force has been investigated by Struik, Oyeledun, and Fisher [16]. Relevant to the current study, it was concluded in this reference that direct tension indicators reliably measure tension even if surfaces under the bolt head and nut are not parallel. Data related to the effect of grip stiffness on tightening by tension control or calibrated wrench methods are not available.

The slip coefficient has also been the subject of extensive study. The magnitude of the slip coefficient is highly dependent on the condition of faying surfaces. Reported slip coefficients vary widely, even for surface conditions described as clean mill scale. The slip coefficient for clean mill scale was reported to be 0.46 in Reference [3], 0.35 in Reference [15], 0.30 in Reference [17], 0.29 in Reference [1], and 0.23 in Reference [20]. In Reference [7] a mean value of 0.33 is calculated from a compilation of 327 tests conducted by numerous researchers. This value of 0.33 is listed in the RCSC Specification as the applicable value for clean mill scale faying surfaces.

The RCSC Specification requires a 15% reduction in slip coefficient when oversize or short slotted holes are used. This reduction is based on research conducted by Allan and Fisher [1] in which it was found that the average slip coefficient for specimens with standard holes was 0.29, while that for specimens with oversize holes was 0.24. This drop in slip coefficient was attributed to compression of surface irregularities near the hole. More compression occurs around oversize holes than standard holes because of the higher contact pressures around the oversize holes. However, in the context of the Allan and Fisher paper, oversize holes for 1-in. bolts had a diameter 5/16 in. larger than the bolt diameter. This hole size is larger than what is currently defined as an oversize hole. Allan and Fisher extrapolated their test results to other bolt diameters on the basis of pressure under the head or nut. According to the current definition of oversize holes in the RCSC Specification, the work of Allan and Fisher does not indicate a reduction in slip coefficient is in order. In References [13] and [20] it was similarly concluded that hole diameter does not affect slip coefficient.

Kulak et al. [7] further justify the reduced slip coefficient for oversize holes in the RCSC Specification on the basis of lower tension in bolts tightened in oversize holes relative to bolts tightened in standard holes. However, Allan and Fisher [1] relate this effect only to turn-of-nut tightening and demonstrate that this decrease in tension does not occur if washers are used under both the head and the nut of bolts installed in oversize holes.

Since the current RCSC Specification requires hardened washers when oversize holes are in the outer plies of a connection, bolt tension should not be reduced. In the present work, only oversize holes are used, so a direct comparison between oversize and standard holes will not be possible.

Several studies have been conducted which are more closely related to the effect of burrs on slip resistance. Vasarhelyi and Chen [18] constructed butt splices with main plates of different thickness. Because the main plates were of different thickness, the splice plates did not come into full contact with the thinner main plate. Vasarhelyi and Chen noted a reduction in slip coefficient for plate thickness differing by 1/16 and 1/8 in.

Lee and Fisher [8] conducted tests with washers or filler plates inserted between main and splice plates. There is some confusion as to the conclusions to be drawn from this work. The Guide references this work and concludes that fillers have no effect on slip coefficient, while in the final report Lee and Fisher state that both washers and fillers cause significant reductions in slip coefficient. There is a possibility that the surfaces of the washers and fillers were smoother than the main and splice plates, which may have led to the low slip coefficients.

As mentioned earlier, Yura, Hansen, and Frank [21] conducted tests on bolted splice connections with undeveloped fillers. Slip coefficients measured in these tests decreased from 0.33 when no filler plate was present, to 0.27 when one 1/4-in. filler was present, to 0.18 when three 1/4-in. fillers were present. Although a reduction in slip coefficient with filler thickness is indicated, it should be noted that the reduction for a 1/4-in. filler is small and that only six specimens were tested in the entire program.

Polyzois and Yura [10] conducted a test program very similar to the current program to determine whether burrs have a detrimental effect on slip resistance in bolted joints. Plates of different thickness and yield strengths were included in the program. Burr heights varied from 0 to 1/8 in. It was concluded that the interlocking of burrs has a beneficial effect on the slip coefficient. Polyzois and Yura maintained tension in their bolts with a hydraulic ram and did not test multiple bolt connections.

On the basis of the past work described above, it is expected that the presence of burrs in a bolted connection will lead to difficulties in achieving the correct tension when turn-of-nut installation is used. Difficulties are not anticipated when direct tension indicators are used. Slip coefficients can reasonably be expected to range between 0.20 and 0.40. The effect of oversize holes on the slip coefficient is expected to be insignificant. The effect of burrs on shear strength and slip coefficient is expected to be dependent on the size of the burr.

CHAPTER 3

EFFECT OF BURRS ON SHEAR CAPACITY IN BEARING CONNECTIONS

3.1 Specimen Preparation

All specimens were constructed from A572 Grade 50 steel plate. A photograph of a typical specimen is shown in Figure 2 and a drawing is provided in Figure 3. Specimens were constructed to match those tested by Wallaert and Fisher [19]. Individual plates comprising the specimens were flame cut from a much larger plate by a local steel fabricator. Plates were trucked to the testing laboratory for cleaning, punching, and bolting.

Cleaning involved chipping slag away from the cut edges of the plate. This slag sometimes extended onto the surface of the plate and could have interfered with contact between faying surfaces. Care was taken not to damage the surface of the plates with the chipping hammer.

Once the edges of the plates had been cleaned, hole locations were marked and the plates were carried to a drill press. The pair of holes seen at the top of the specimen in Figures 2 and 3 were formed by drilling. These holes were not the test holes and any burrs resulting from the drilling operation were removed by grinding. The single hole at the bottom of the specimen was formed by first drilling through approximately half the plate thickness and then punching the remainder of the way through the plate.

Punching was carried out in a universal test machine outfitted with a 13/16-in. punch and a 7/8-in. die. A photograph of the setup is shown in Figure 4. It was necessary to complete the holes with a punch, instead of drilling completely through the plate, to form desired burr sizes. The hole was not formed completely by punching because it is not possible to punch a 13/16-in. hole in a 1-in. thick grade 50 steel plate.

Burr size was controlled by the condition of the cutting edge on the die. In the as-received condition, the die produced thin, irregular shaped burrs with maximum heights ranging from 1/32 to 1/16 in. Larger burrs were produced by punching holes through a die with a beveled cutting edge. A 1/16-in., 45° bevel cut around the inside diameter of the die

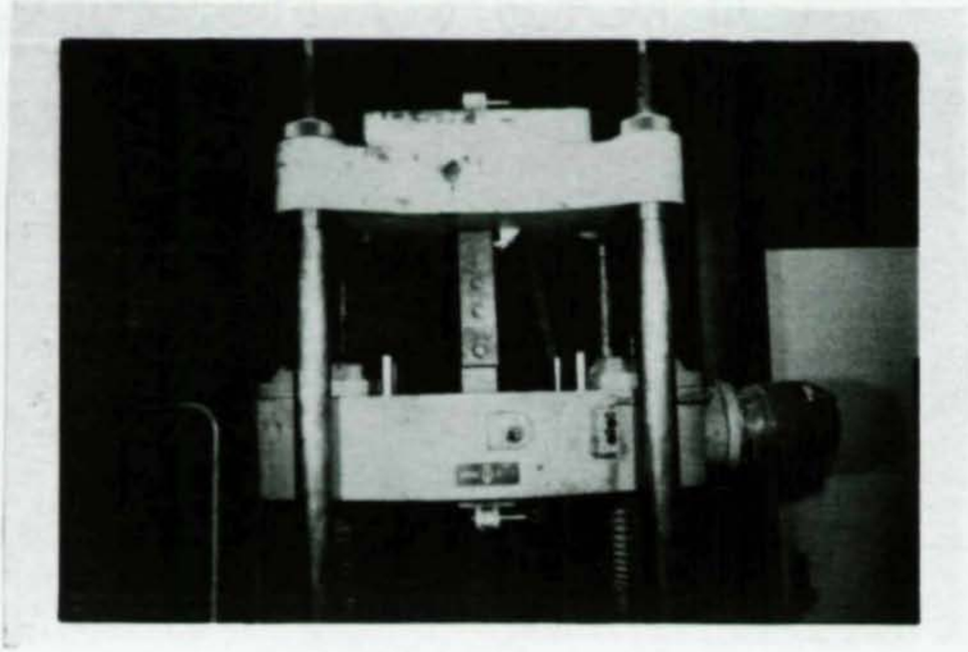

Figure 2. Photograph of Bearing Connection Specimen

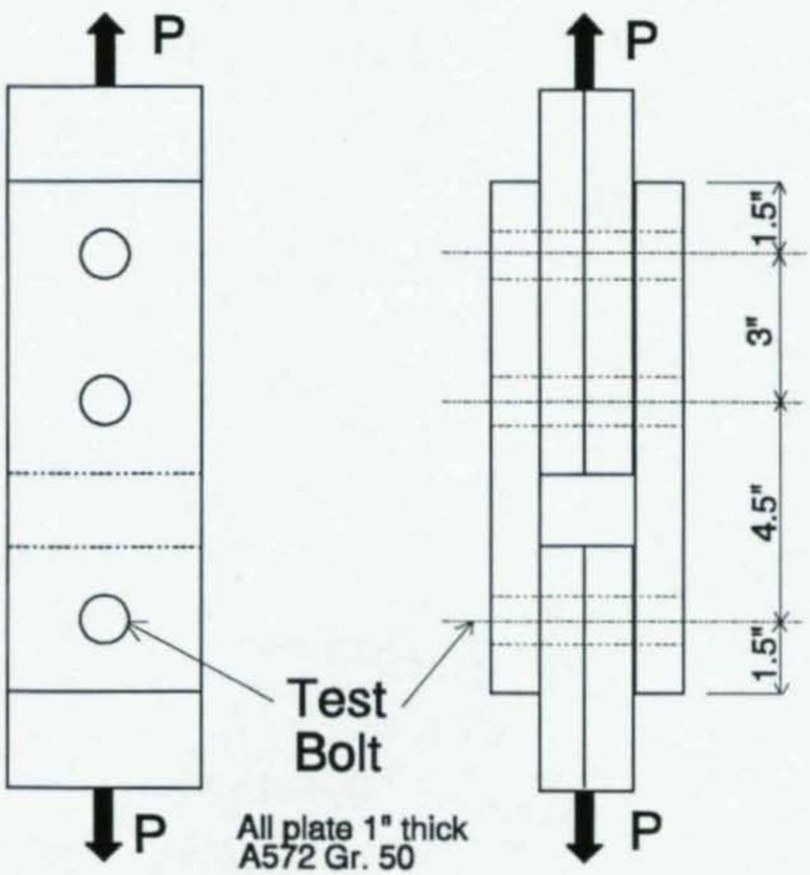

Figure 3. Drawing of Bearing Connection Specimen

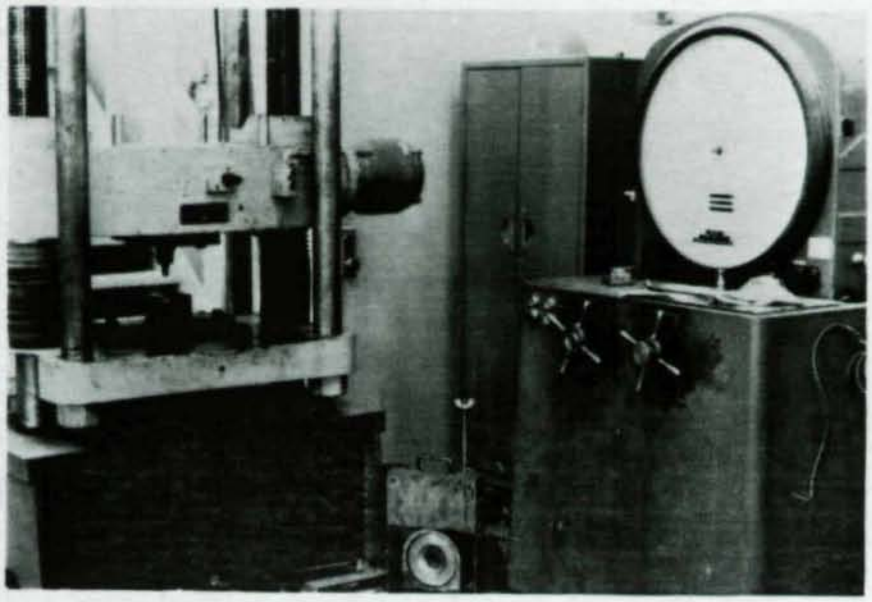

Figure 4. Hole-Punching Equipment

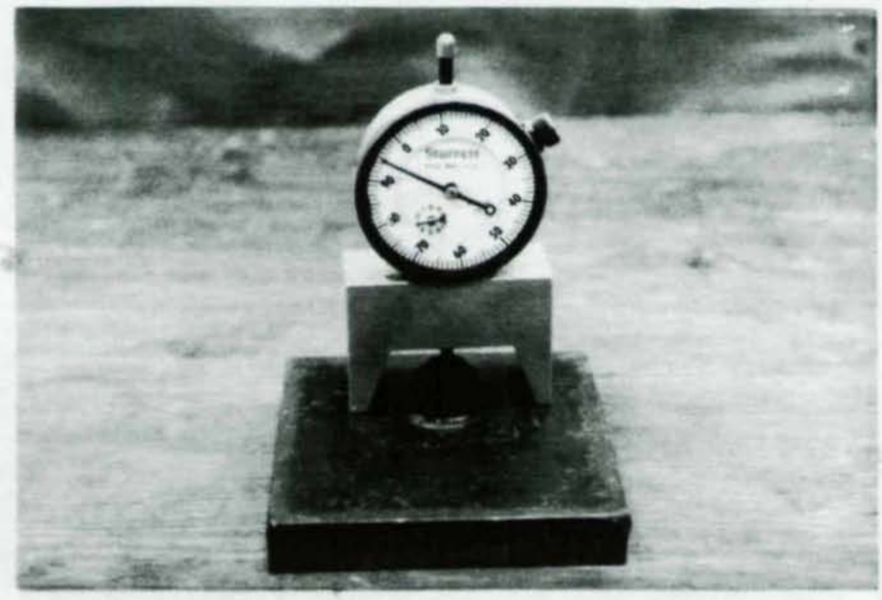

Figure 5. Measurement of Burr Height

caused burrs approximately 1/16 in. in height to form completely around the hole. A 1/8 in., 30° bevel produced burrs slightly larger than 1/8 in.

Plates for control specimens were taken from the group of plates punched with the die in the as-received condition. For the control specimens, burrs were removed by grinding. To the extent possible, grinding was restricted to the burr. An effort was made to avoid damaging or modifying the plate surface away from the hole.

Specimens were cleaned by wiping with a dry rag. No attempt was made to completely remove cutting oil from specimen surfaces. Since these plates would be used in bearing connections, any oil present would have the desirable effect of reducing friction between faying surfaces.

The final step before testing involved measuring burr heights. Burr heights were measured using a dial indicator as shown in Figure 5. The maximum burr height was located by moving the dial indicator around the hole. When the maximum height was determined, this value was recorded and burr heights were measured and recorded for positions 90, 180, and 270°, from the maximum burr. Burr heights for holes punched through beveled die were reasonably consistent in terms of size and shape around the hole; there was no tendency to have a large burr on one side of the hole and no burr on the other.

3.2 Test Procedure

The top two plates in Figures 2 and 3 were clamped into the upper crosshead with their boltholes aligned. The two bottom plates were dropped into the lower crosshead with their burrs facing out. The two plates at midheight were loosely bolted to the two upper plates. To prevent burr orientation on the midheight plates from biasing the data, in half the tests the burrs on these plates faced in toward the center of the specimen and in half the tests the burrs faced out. When the midheight plates had been attached to the top plates, the bottom crosshead was raised or lowered until the test bolt could be inserted into the single hole through the midheight and bottom plates. All nuts were tightened by hand. The bottom plates were then centered in the lower grip and clamped into the crosshead.

To quantify the extent to which the burrs forced the connected plates apart, the grip in the vicinity of the test bolt was measured with a dial caliper. The average of two measurements made on opposite sides of the bolt for each specimen are plotted versus burr height in Figure 6. The burr height plotted is the average of the maximum burr height on each of the four connected plates. As expected, the grip increases as burr height increases. The separation of faying surfaces produced by the burrs can be seen in Figure 7 for a specimen with an average maximum burr height of approximately 1/8 in.

When the specimen was set in the grips, load was continuously applied to failure. Failure was always defined as the shearing off of the single test bolt. Some ovaling did occur in the single bolt hole, but never enough to be regarded as a bearing failure. At the conclusion of the test, the load at failure was recorded, the midheight and lower plates were removed and replaced with new plates, and the process was repeated.

3.3 Results and Discussion

Results of the tests are listed in Table 1 and plotted in Figure 8. Shear stresses are calculated assuming both shear planes are in the unthreaded portion of the bolt. This assumption was correct for all but a few of the specimens with the largest burrs. In cases where the grip exceeded 4-1/2 in., the inside surface of one of the outer plates fell on the threaded portion of the bolt. However, assuming that both shear planes are fully on the unthreaded shank results in a conservative calculated failure stress.

Also shown in Figure 8 are a line representing the shear strength of A325 bolts [7], a linear regression line fit to the data, and the 99% confidence limits for the regression. Notice that shear strengths for specimens with no burrs are larger than the published value. As burr size increases there is a slight decrease in shear strength.

The data are replotted in Figure 9 using only specimens with burr heights less than 1/16 in. The downward slope of the regression line for this portion of the data is almost imperceptible. Considering the fact that the mean shear strength decreases by only 2.4% as the burr height rises from 0 to 1/16 in., and that all nuts were hand tightened, it is concluded that burr heights of 1/16 in. or less are permissible in a bearing connection. It should also be noted that only one data point falls below the AISC specified 72 ksi nominal

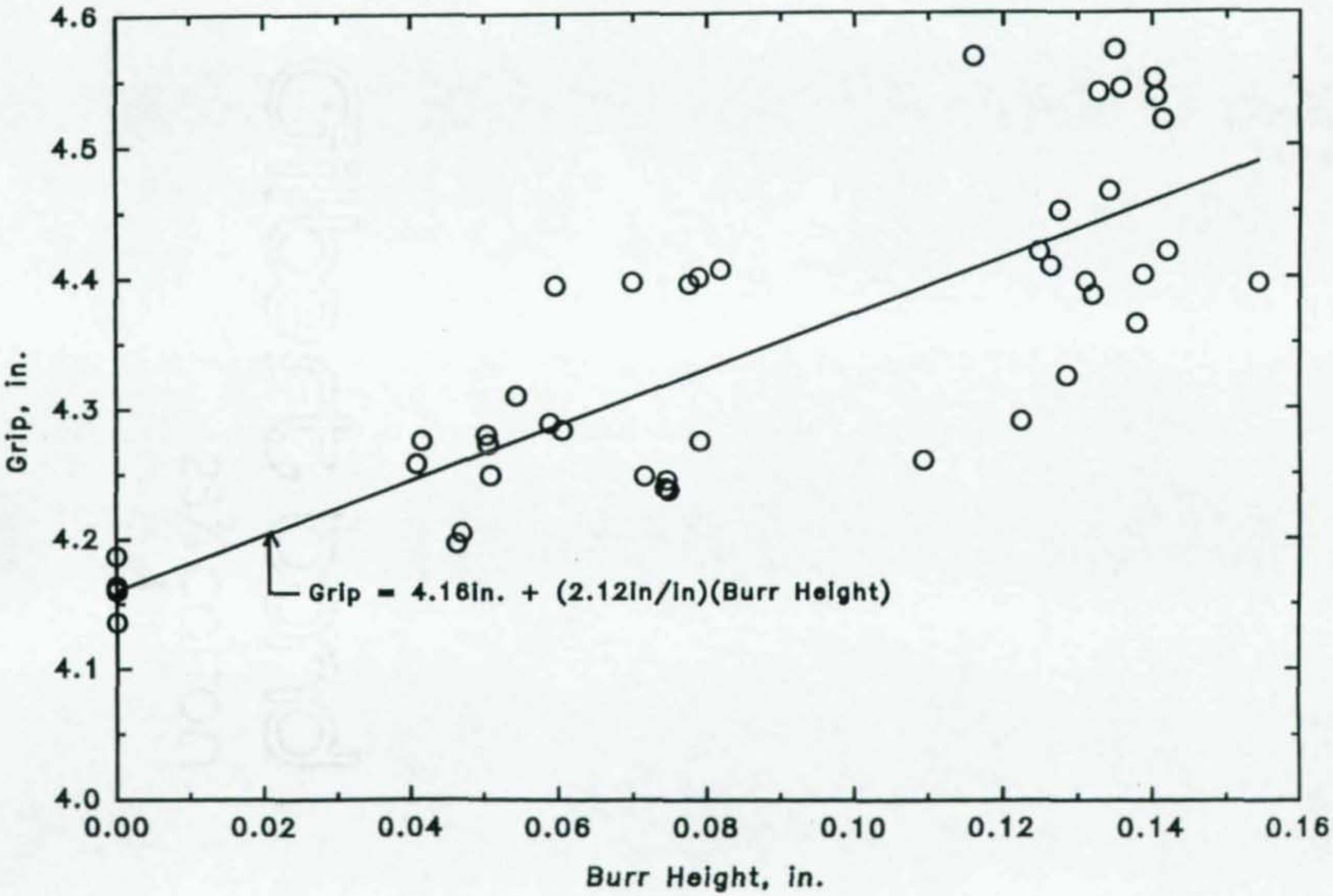

Figure 6. Grip Versus Burr Height for Bearing Specimens

Figure 7. Separation of Faying Surfaces on Bearing Specimen

TABLE 1. SHEAR CAPACITY IN BEARING CONNECTIONS

Specimen Number	Burr Height, in.	Failure Stress, kips
1	0.0000	84.3
2	0.0000	84.3
3	0.0000	84.9
4	0.0000	86.0
5	0.0000	84.0
6	0.0543	69.7
7	0.0508	88.2
8	0.0408	84.3
9	0.0415	86.5
10	0.0503	83.4
11	0.0463	85.4
12	0.0470	77.9
13	0.0588	93.9
14	0.0505	84.9
15	0.0605	81.4
16	0.0698	81.5
17	0.0775	80.9
18	0.0595	79.8
19	0.0818	74.2
20	0.0788	85.4
21	0.0748	87.6
22	0.0745	85.9
23	0.0790	80.8
24	0.0715	81.7
25	0.0743	85.0
26	0.1350	72.4
27	0.1403	76.7
28	0.1358	75.0
29	0.1328	82.1
30	0.1415	91.7
31	0.1388	78.5
32	0.1263	78.1
33	0.1420	76.6
34	0.1543	76.8
35	0.1320	84.9
36	0.1248	86.0
37	0.1160	84.3
38	0.1343	83.2
39	0.1275	89.0
40	0.1405	78.1
41	0.1380	78.1
42	0.1310	82.1
43	0.1285	77.2
44	0.1223	82.6
45	0.1093	76.5

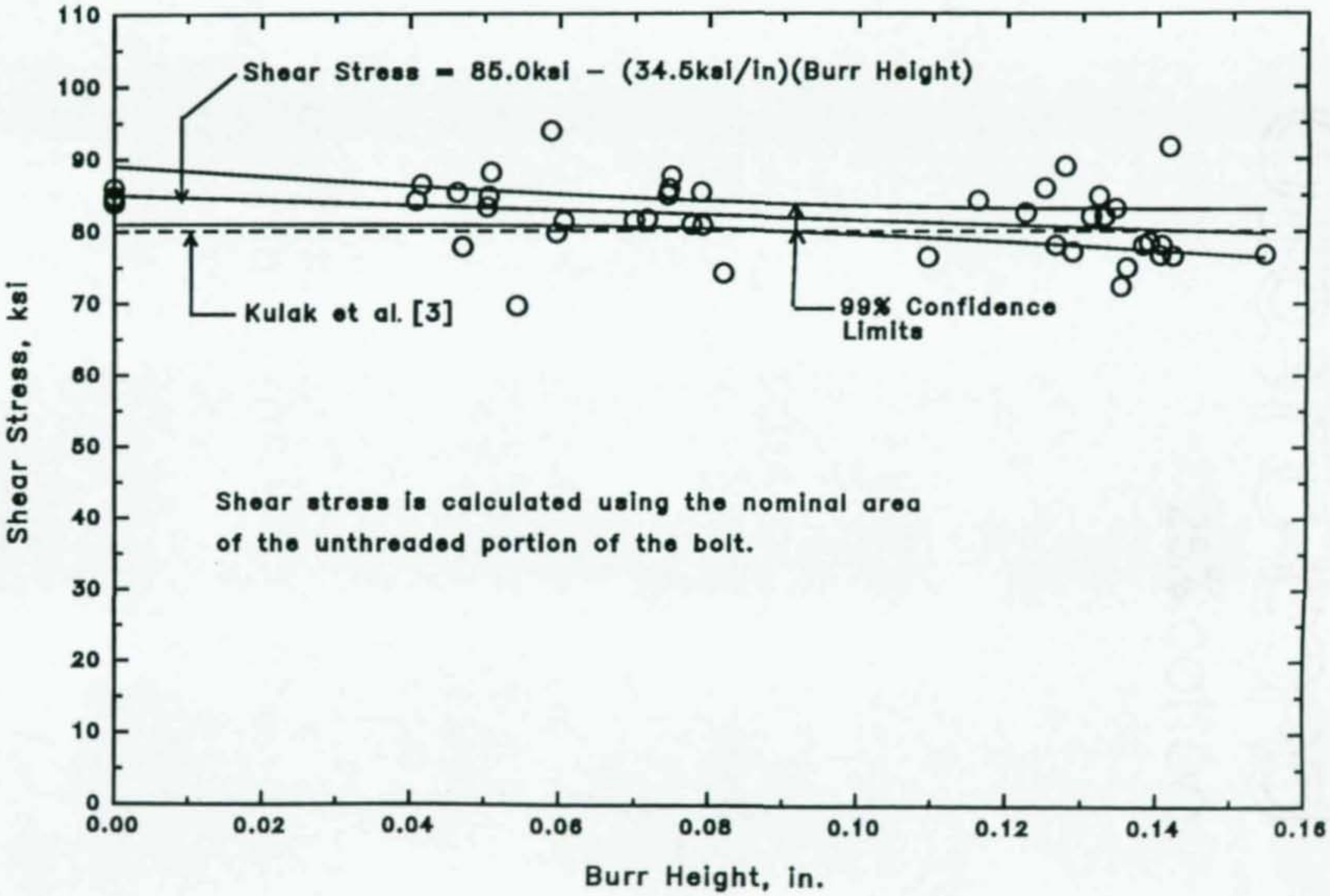

Figure 8. Shear Stress Versus Burr Height for Bearing Connections

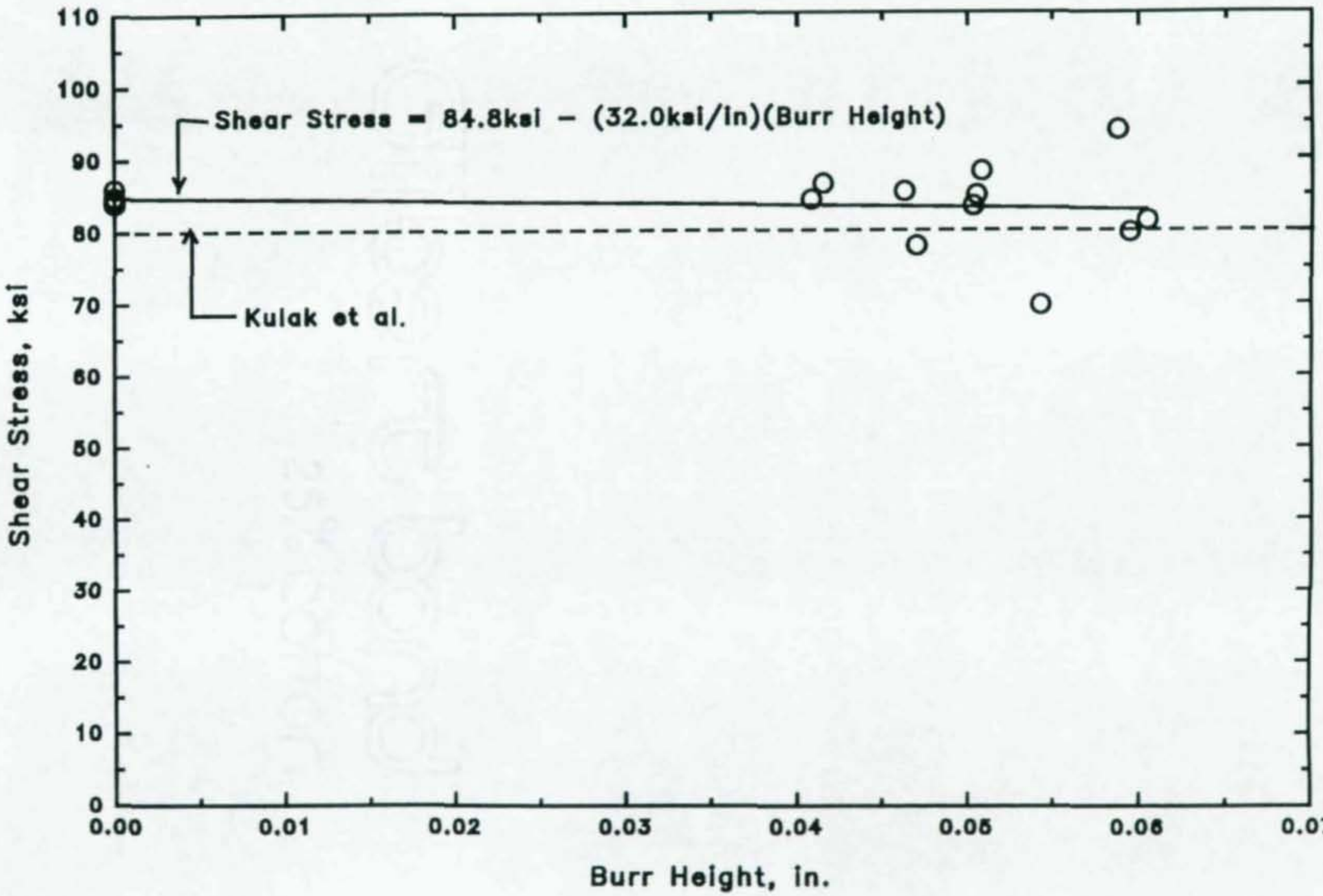

Figure 9. Shear Stress Versus Burr Height for Bearing Connections With Burrs Smaller Than 1/16 in.

shear strength for A325 bolts in bearing connections with threads excluded from the shear plane. The regression line lies well above this limit for the full range of burr heights tested.

CHAPTER 4

EFFECT OF BURRS ON BOLT TENSION IN FRICTION CONNECTIONS

4.1 Specimen Preparation

A photograph of a typical specimen is shown in Figure 10 and a drawing is provided in Figure 11. Similar to the bearing connections described in the preceding chapter, all specimens were constructed with pieces flame-cut from a large A572 Grade 50 steel plate. Edges of the specimen were cleaned by grinding; care was taken not to damage the plate surface during cleaning.

Holes were punched on a 300-kip capacity universal test machine outfitted with a 15/16-in. punch and a 1-in. die. This hole size is defined as oversize for the 3/4 in. diameter bolts used in this study. As described in the preceding chapter, burr size was controlled by varying the bevel on the inside of the die. Plates for control specimens were prepared by grinding burrs from around holes punched with the die in the as-received condition. Burr heights were measured and recorded as described in the preceding chapter.

Specimens were cleaned by washing with an industrial solvent (trade name Ultra Solve) and air drying. The solvent evaporated rapidly without leaving a residue on the plate.

4.2 Test Procedure

Specimens were tested by bolting three plates to the front of the Skidmore-Wilhelm calibration device as illustrated in Figures 10 and 11. Plates with approximately the same burr height were used to form a single specimen. Bolt tension was read directly from the Skidmore-Wilhelm. The calibration of the Skidmore-Wilhelm was checked prior to beginning the test program, at approximately the midpoint of the test program, and at the conclusion of the test program.

To better simulate field conditions, relative motion of the plates was restricted by placing a loose-fitting steel frame around the plates prior to tightening. The rectangular frame can be seen in Figure 10. The frame prevents the burrs from sliding over each other

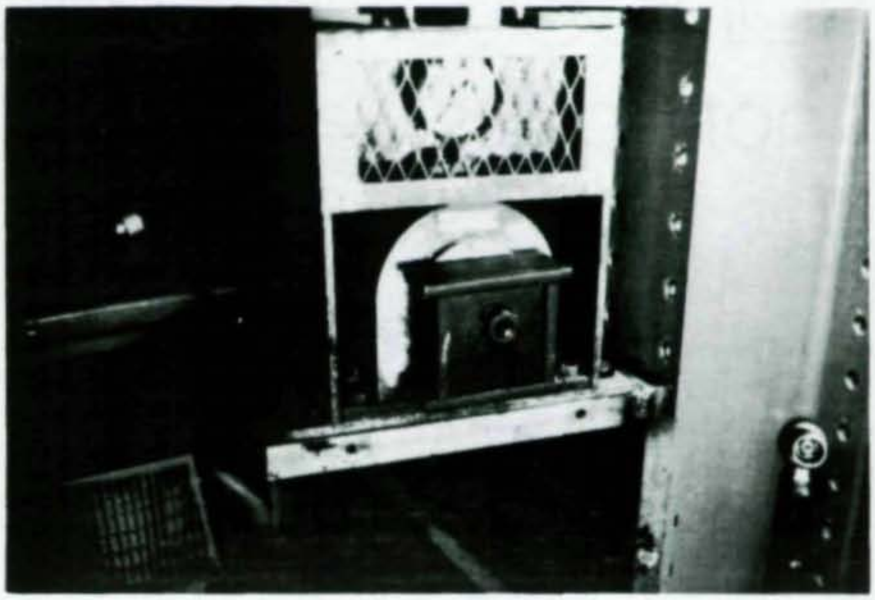

Figure 10. Photograph of Specimen Used to Measure Bolt Tension

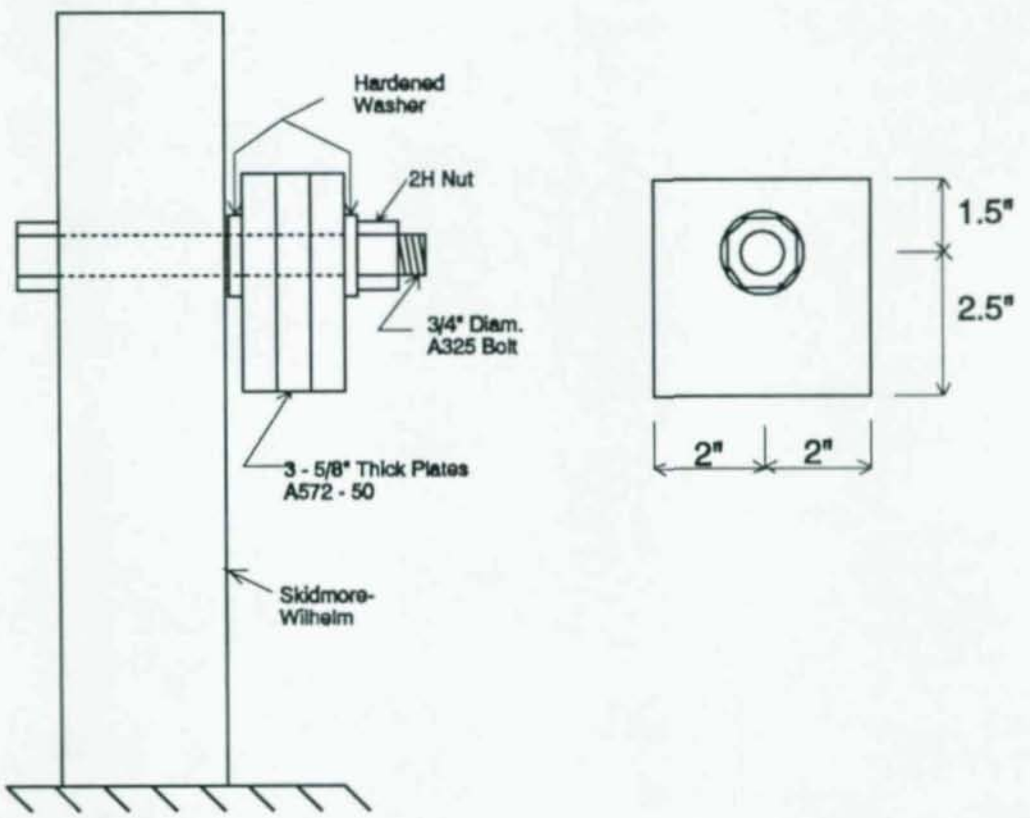

Figure 11. Schematic of Specimen Used to Measure Bolt Tension

during tightening. In practice, this sliding would be restricted by other bolts in the connection.

An approximately equal number of specimens were tested by tightening bolts using turn-of-nut, tension control, direct tension indicator, and calibrated wrench methods. For all methods except tension control, bolts were tightened with a torque wrench. Incremental tightening with a torque wrench as opposed to continuous tightening with a pneumatic wrench should not affect test results [5, 12].

4.2.1 Turn-of-Nut

The RCSC Specification requires nuts to be turned to the snug-tight condition prior to being fully tensioned by turning some specified amount. The RCSC Specification defines snug as the tightness that exists when all plies in a joint are in firm contact, then continues by stating that this tightness may be attained by a few impacts of an impact wrench or the full effort of a man using an ordinary spud wrench. Previous research has defined bolt tension at snug as 5 kips [16], 8 kips [5, 6, 12], and 10 kips [14].

In an attempt to reconcile research and practical definitions of snug, the average torque required to produce 8 kips tension in five different bolts is defined as snug for this study. This torque averaged 105 ft-lbs as measured with a 150 ft-lb torque wrench. Bolt tension at 105 ft-lbs is plotted versus burr height in Figure 12. The decline in tension with increasing burr height is small and the scatter in the data does not appear to be influenced by burr height.

Once the nut was snug, a rectangular magnetic sheet containing a hole slightly larger than the hardened washer was placed on the plate around the nut. Marks were placed around the hole in the sheet in 5° increments. The nut was marked at the zero position, and nut rotation and bolt tension were recorded during tightening. A photograph of this measuring device is provided in Figure 13.

For the bolt length and diameter used in these tests, the RCSC Specification requires a nut rotation of 180° past snug to insure proper pretension. This approach worked well in the current tests as long as the burr was small. When large burrs were present, additional turns were required to compress the burrs before bolts could be properly pretensioned.

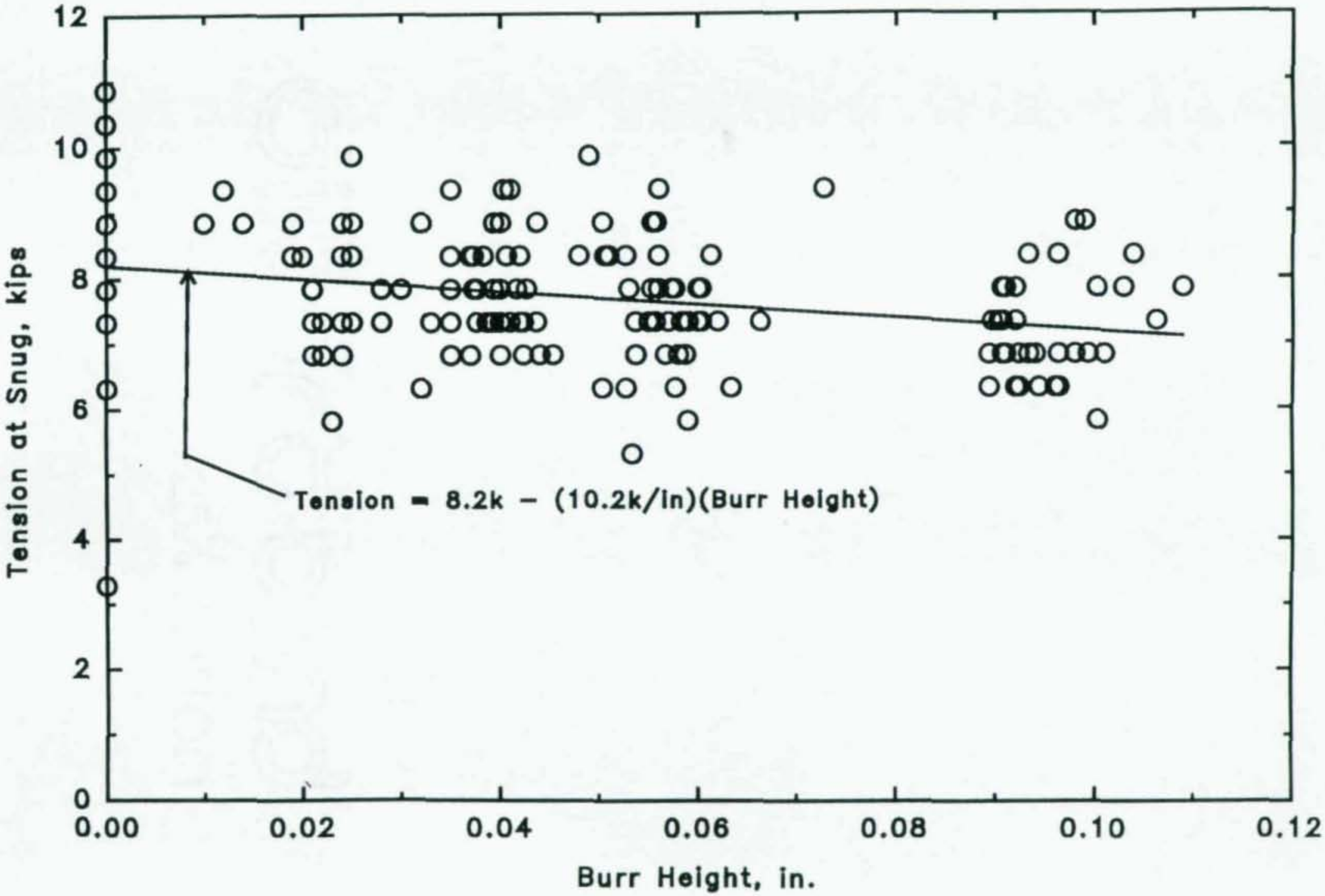

Figure 12. Bolt Tension at Torque of 105 Ft-Lbs

Figure 13. Device to Measure Nut Rotation

To determine the amount of rotation required to achieve the correct pretension, each bolt with large burrs was tightened to three different levels. First, nuts were turned 180° past snug and the tension was recorded. Second, nuts were turned until the minimum specified pretension of 29.4 kips was achieved and rotation was recorded. (This tension includes the 5% excess above the required fastener tension.) Third, nuts were turned until the same average tension produced in specimens with no burr (35.6 kips) was produced in these specimens, and the rotation was recorded. Plots of rotation versus burr size for each of the three tension levels are shown in Figures 14, 15, and 16.

In Figure 14, especially note the data points identified as "Die As-Received." These burrs were produced before the cutting edge on the die was beveled and tended to be thinner and more irregular than burrs produced with the beveled die. These thin burrs have much less influence on bolt tension than the burrs intentionally produced, even when they are of the same average maximum height.

4.2.2 Tension Control

Tension control bolts were installed according to RCSC specifications. The bolts were tightened to the snug condition using a torque wrench. The snug tension was recorded and the nut was marked at the zero rotation position. Final tightening was accomplished using a tension control wrench. When the splined end twisted off the bolt, the wrench was removed and bolt tension and nut rotation were recorded.

Difficulties in operating the tension control wrench occurred when burr heights exceeded approximately 0.10 in. The splined end of the bolt must reach a minimum distance into the wrench before the wrench will operate properly. When large burrs were present it was sometimes necessary to tighten the nut slightly above snug with the torque wrench to compress the burrs and allow the splined end to reach into the gun as required.

4.2.3 Direct Tension Indicators

Direct tension indicators were installed according to RCSC and manufacturer's specifications. The indicators were placed between the head of the bolt and a hardened washer. Bolts were tightened to the snug condition using a torque wrench, the snug tension was recorded, and the nut was marked at the zero rotation position. Final

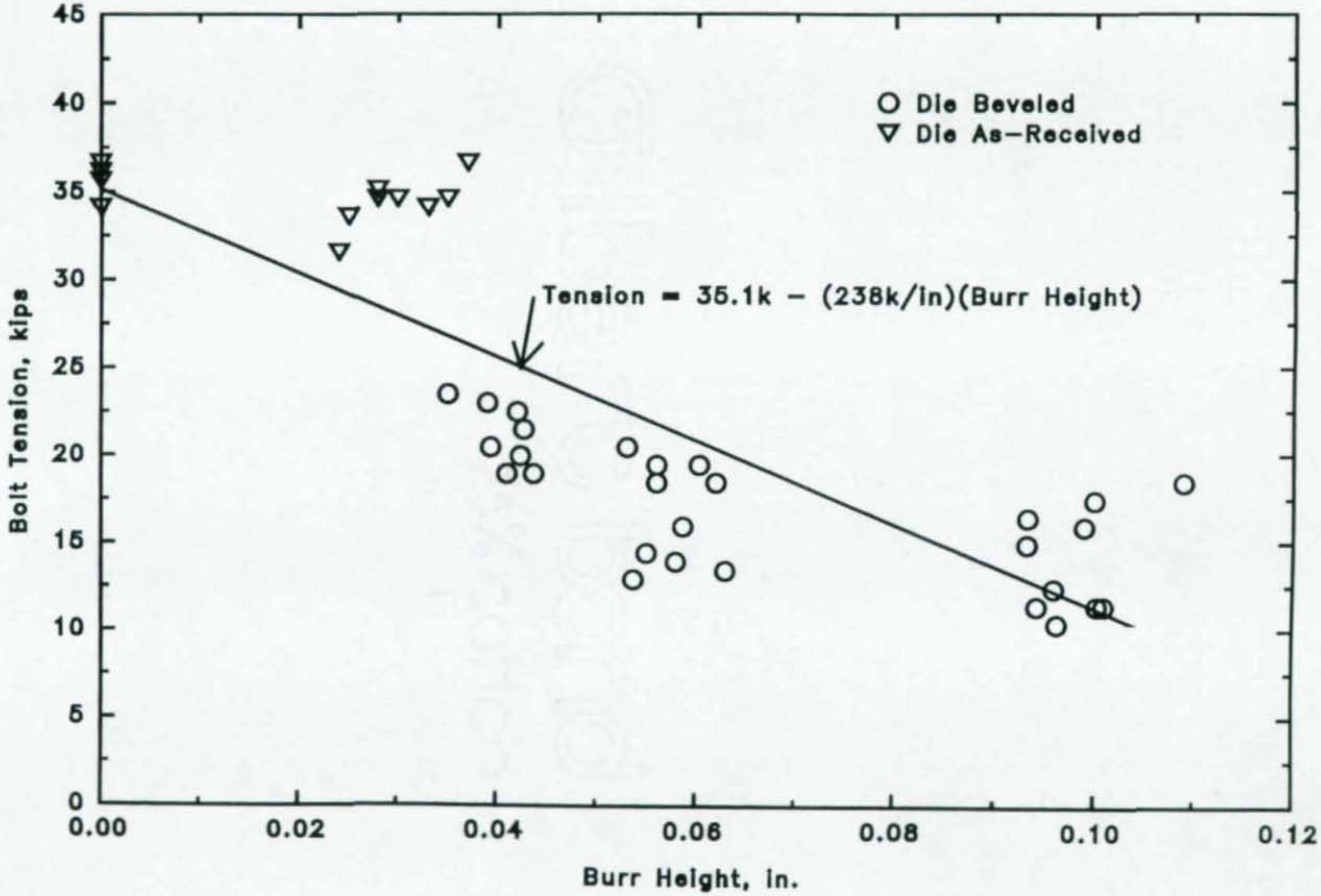

Figure 14. Bolt Tension With Nut Rotated 180° Past Snug

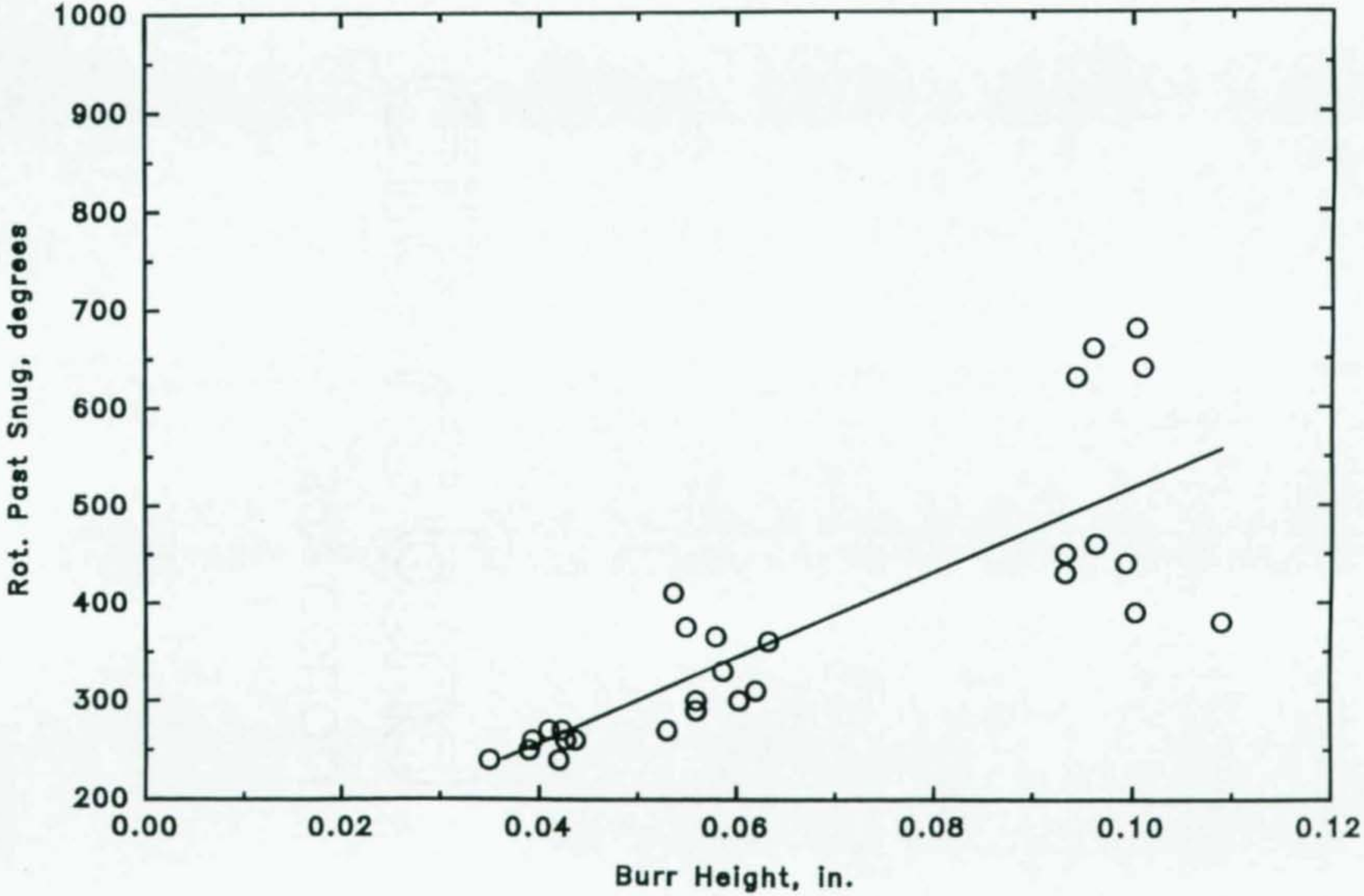

Figure 15. Nut Rotation Required to Produce 29.4-Kips Tension

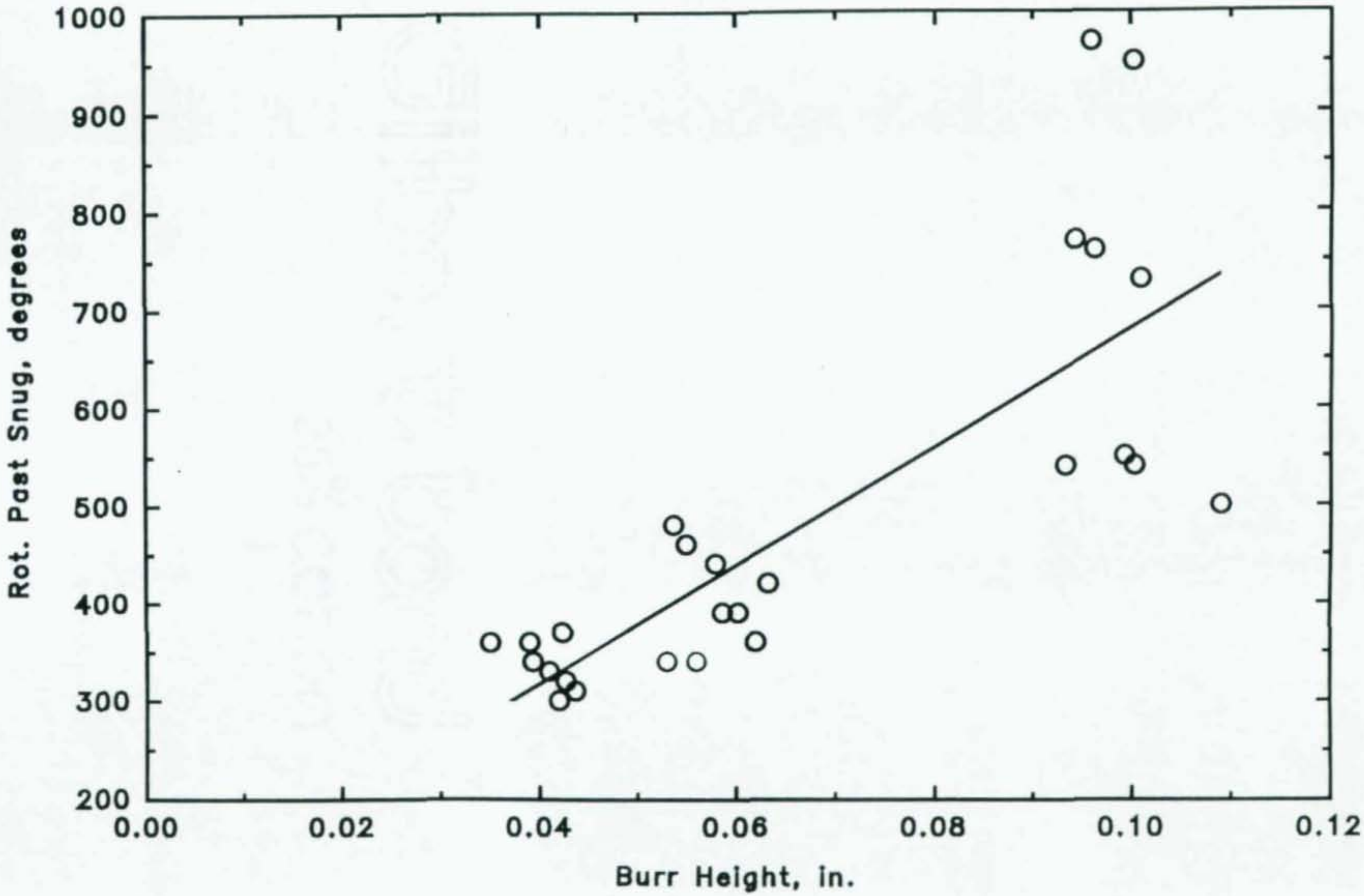

Figure 16. Nut Rotation Required to Produce 35.6-Kips Tension

tightening was accomplished using a 600 ft-lb torque wrench. Space between the direct tension indicator and the head of the bolt was monitored with a feeler gage. As specified by the manufacturer, when a 0.015-in. gage could not be inserted into three of the five available spaces between the direct tension indicator and the head of the bolt, the bolt was considered to be pretensioned.

In all tests except those with direct tension indicators, the bolt was first inserted through the Skidmore-Wilhelm and then through the plates so that the head of the bolt was restrained by the Skidmore-Wilhelm and the nut was on the outside of the plates. In all tests with direct tension indicators, it was necessary to reverse the bolt direction so that the gaps in the indicator could be accessed with the feeler gage. This orientation made it necessary to have one person restrain the bolt from rotating by holding the head with a wrench, while another person on the back side of the Skidmore-Wilhelm turned the nut. Bolt orientation should not affect tension measured with the Skidmore-Wilhelm.

4.2.4 Calibrated Wrench

The calibrated wrench installation procedure followed RCSC specifications. Three bolts of the same diameter, length, and grade as those used in the tests were tightened to the required 29.4 kips tension using a 600 ft-lb torque wrench. The torque applied to produce the required tension averaged 350 ft-lbs for the three bolts tested. In all tests using the calibrated wrench, nuts were first tightened to snug and nut position was marked, followed by final tightening to 350 ft-lbs. Bolt tension and nut rotation past snug were recorded.

4.3 Results and Discussion

Bolt tension versus burr height data are listed in Table 2 and plotted in Figures 17 through 20 for each of the four installation techniques described above. A regression line and the tension required by the RCSC Specification including the 5% excess is also plotted in each of these figures. Data for all techniques are presented on one plot in Figure 21.

The principal conclusion to be drawn from examination of Figures 17 through 21 is that tension produced using tension control bolts or direct tension indicators is not affected

TABLE 2. BOLT TENSION

Specimen Number	Burr Size, in.	Tension, kips	Specimen Number	Burr Size, in.	Tension, kips
301	0.000	36.6	351	0.021	31.1
302	•	•	352	0.014	31.6
303	0.000	34.1	353	0.012	32.1
304	0.000	36.1	354	0.010	31.1
305	0.000	35.6	355	0.019	29.6
306	0.000	30.4	356	0.024	31.6
307	0.000	32.6	357	0.019	32.6
308	0.000	30.1	358	0.022	30.1
309	0.000	29.6	359	0.021	29.1
310	0.000	29.6	360	0.022	29.6
311	0.000	28.6	361	•	•
312	0.000	28.6	362	0.042	22.5
313	0.000	27.5	363	0.039	23.0
314	0.000	29.4	364	0.035	23.5
315	0.000	29.1	365	•	•
316	0.000	32.6	366	0.042	20.0
317	0.000	33.1	367	0.041	19.0
318	0.000	31.1	368	0.044	19.0
319	0.000	31.1	369	0.043	21.5
320	0.000	30.6	370	0.039	20.5
321	0.030	34.6	371	0.039	32.1
322	0.030	34.6	372	0.040	31.6
323	•	•	373	0.039	31.1
324	0.028	35.1	374	0.042	31.6
325	0.028	34.6	375	0.041	31.6
326	0.025	33.6	376	0.044	32.6
327	0.033	34.1	377	0.048	32.6
328	0.024	31.6	378	0.049	32.6
329	0.037	36.6	379	0.045	29.6
330	0.035	34.6	380	0.040	33.1
331	0.035	30.6	381	0.035	31.1
332	0.032	32.6	382	0.039	29.1
333	0.035	31.1	383	•	•
334	0.030	29.6	384	0.042	29.6
335	0.020	30.6	385	0.041	29.1
336	0.025	31.1	386	0.039	27.0
337	0.024	32.6	387	0.038	30.6
338	0.025	32.1	388	0.040	29.6
339	0.025	31.1	389	0.042	27.5
340	0.025	33.6	390	0.042	31.6
341	•	•	391	0.040	30.6
342	•	•	392	0.040	26.5
343	•	•	393	0.039	27.5
344	0.023	29.6	394	0.037	29.1
345	0.022	29.6	395	0.038	27.0
346	0.032	29.6	396	0.037	31.6
347	0.044	29.6	397	0.038	31.6
348	0.037	29.6	398	0.041	27.5
349	0.024	28.6	399	0.040	28.1
350	0.021	32.1	400	0.037	31.6

TABLE 2. (Continued)

Specimen Number	Burr Size, in.	Tension, kips	Specimen Number	Burr Size, in.	Tension, kips
401	0.056	19.5	441	0.099	15.9
402	0.062	18.4	442	0.100	17.4
403	0.053	20.5	443	0.109	18.4
404	0.060	19.5	444	0.093	16.4
405	0.056	18.4	445	0.093	14.9
406	0.055	14.4	446	0.096	10.4
407	0.058	13.9	447	0.101	11.4
408	0.054	12.9	448	0.100	11.4
409	0.063	13.4	449	0.094	11.4
410	0.059	15.9	450	0.096	12.4
411	0.060	31.6	451	0.096	31.1
412	0.056	29.6	452	0.092	27.0
413	0.056	32.6	453	0.099	30.6
414	0.050	28.1	454	0.103	31.6
415	0.056	29.6	455	0.098	34.6
416	0.066	31.1	456	0.104	30.6
417	0.055	35.1	457	0.097	30.1
418	0.073	35.1	458	*	*
419	0.056	28.6	459	*	*
420	0.053	32.1	460	*	*
421	0.051	29.6	461	*	*
422	0.057	28.6	462	0.094	27.5
423	0.055	30.1	463	0.092	31.6
424	0.061	30.1	464	0.098	30.6
425	0.057	29.6	465	0.091	30.6
426	0.060	31.6	466	0.096	27.5
427	0.059	32.6	467	*	*
428	0.053	30.1	468	0.090	26.5
429	0.057	26.5	469	0.091	29.1
430	0.058	29.1	470	0.092	31.6
431	0.060	25.0	471	0.106	24.0
432	0.054	24.0	472	0.091	25.5
433	0.054	27.5	473	0.092	24.0
434	0.058	30.1	474	0.092	22.5
435	0.054	23.5	475	0.091	24.0
436	0.058	27.0	476	0.091	26.0
437	0.056	30.1	477	0.090	22.0
438	0.053	30.1	478	0.089	30.6
439	0.059	28.1	479	0.089	21.5
440	0.050	29.1	480	0.092	25.0

*Tests not conducted due to shortage of materials, or error in procedure caused test to be invalid.

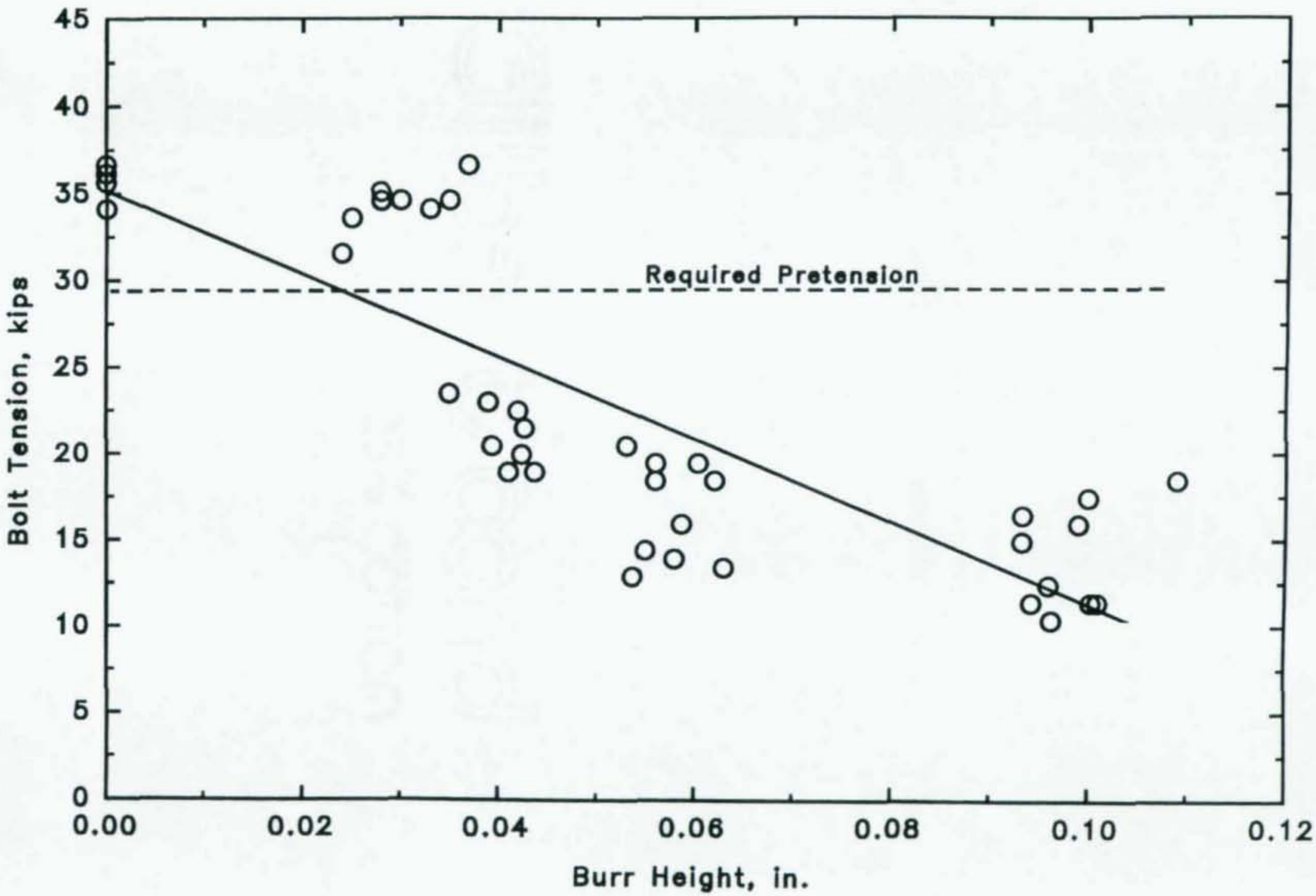

Figure 17. Bolt Tension for Turn-of-Nut Method

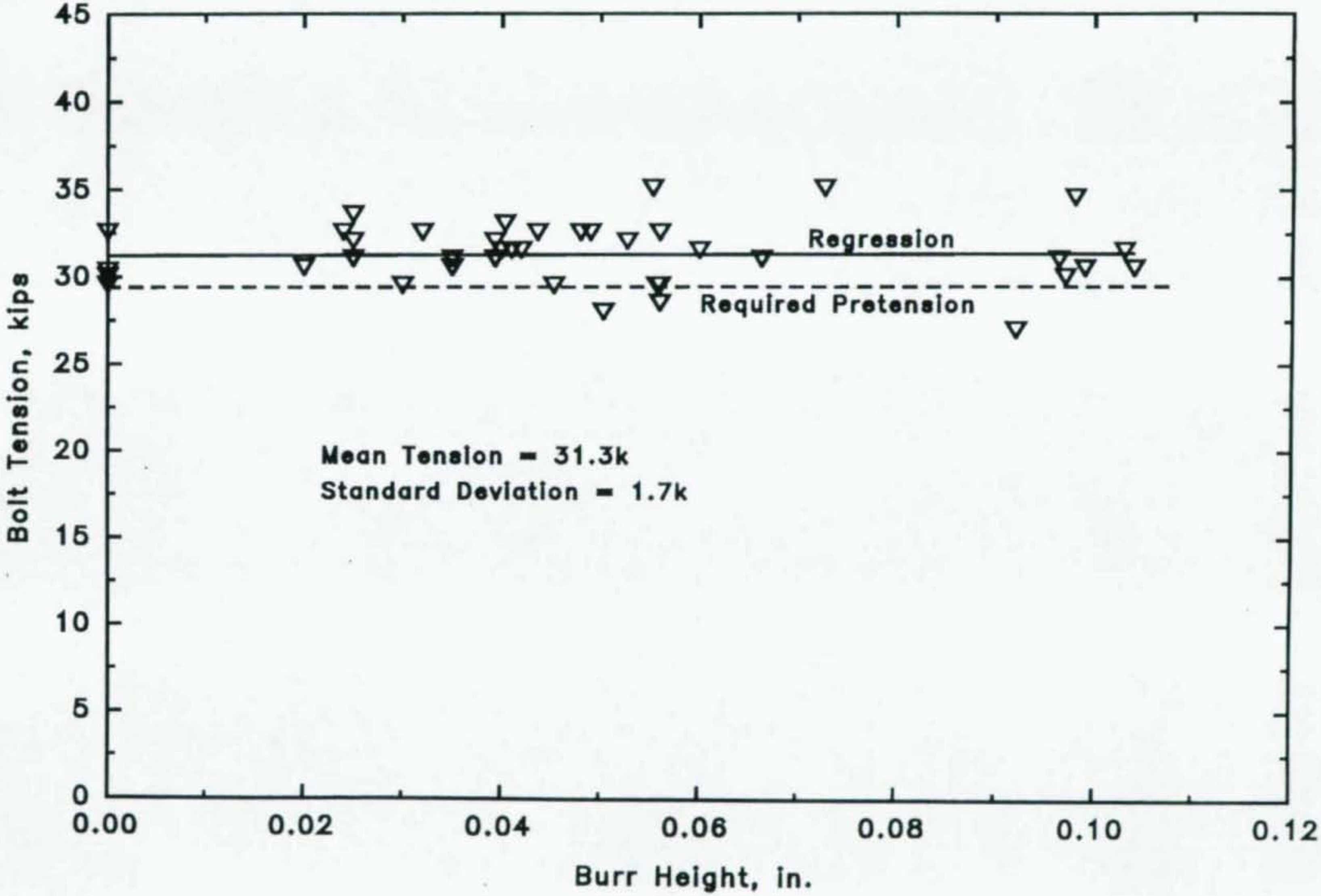

Figure 18. Bolt Tension for Tension Control Installation

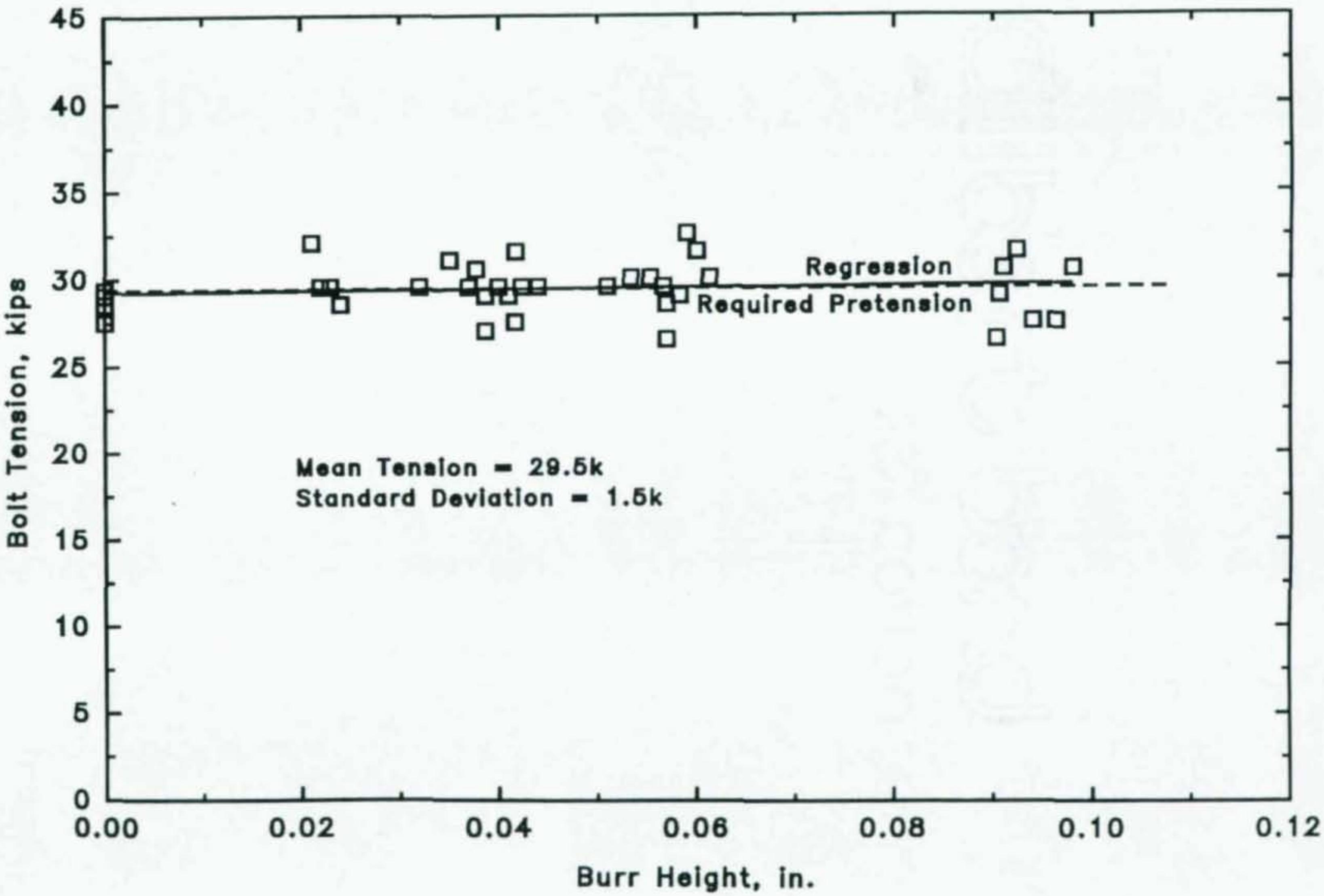

Figure 19. Bolt Tension With Direct Tension Indicators

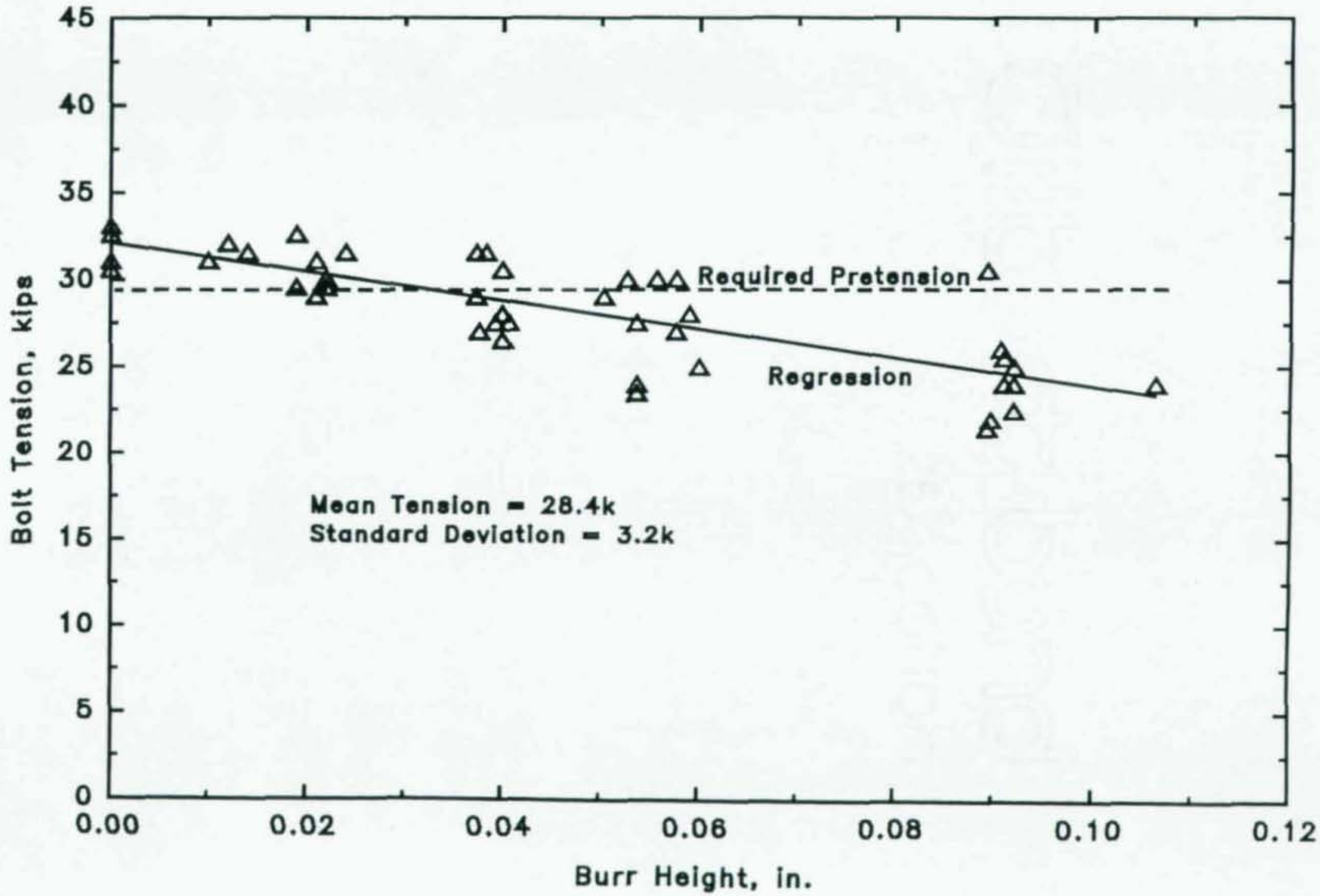

Figure 20. Bolt Tension for Calibrated Wrench Method

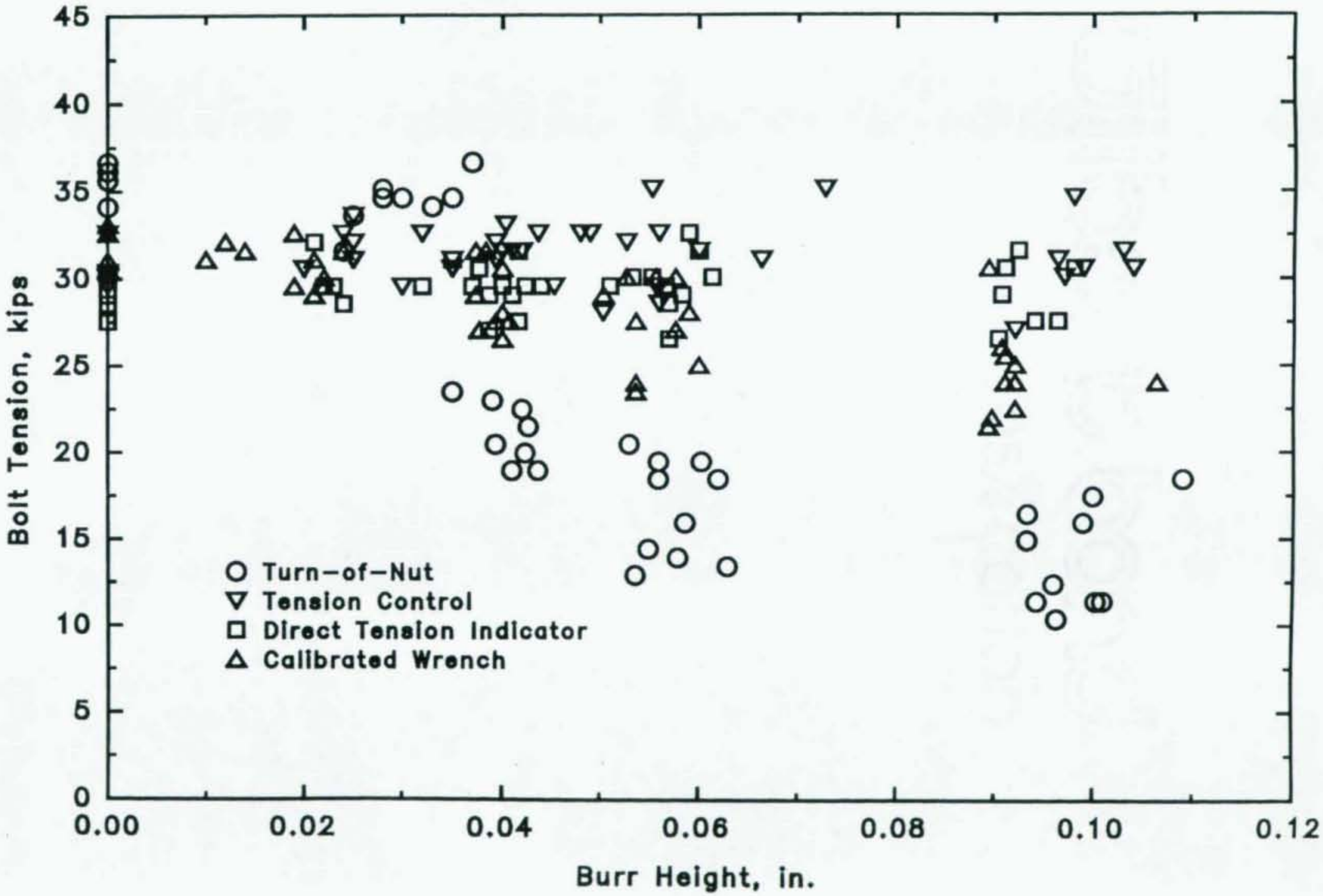

Figure 21. Bolt Tension Versus Burr Height for All Tightening Methods

by burr height. Tension is strongly affected by burr height when the turn-of-nut method is used and is weakly affected by burr height when the calibrated wrench method is used.

It should also be noted that tensions achieved on the basis of direct tension indicator measurements regularly fall below the required tension, even for specimens with burrs removed by grinding. This may have been caused by an attempt on the part of the researchers to be as precise as possible with gap measurements. When the gap began to approach the desired limit, tightening progressed in very small increments with gap measurements made between each increment. Tightening stopped as soon as three of the five gaps would no longer accept the feeler gage. In a field setting, the tendency would be to cut down on the number of measurements by initially overtightening [16]. In relation to the present research, the important point to be made is that bolt tension is not affected by burr height if the bolt is installed using a direct tension indicator. Minor adjustments in procedure would raise the tension consistently above the required level.

In the case of the turn-of-nut method, bolt tensions plotted in Figures 17 and 21 were recorded at a nut rotation of 180° past snug. It has been recommended [10] that when large burrs are present, the procedure for tightening bolts when both faces of the bolted parts are sloped not more than 1:20 from bolt axis [11] be used. In the present case, this would require a rotation of 300° past snug. Referring to Figure 15, it can be seen that a rotation of 300° past snug does not insure proper tension. It would be very difficult to establish a set nut rotation to be used when large burrs are present. The difficulty would be compounded when the number of plates in the grip varied from that used in these tests.

CHAPTER 5

EFFECT OF BURRS ON SHEAR CAPACITY IN FRICTION CONNECTIONS

5.1 Specimen Preparation

Individual plates were cut, cleaned, and punched as described in the preceding chapter. Specimens were constructed from individual plates following the recommendations of Yura and Frank [22]. Both one-bolt and four-bolt specimens were tested. One-bolt specimens were constructed with 3/4-in. diameter A325 bolts and with 1-in. diameter A490 bolts; four-bolt specimens were constructed with 3/4-in. diameter A325 bolts. A drawing of a one-bolt specimen is provided in Figure 22 and of a four-bolt specimen is provided in Figure 23.

To keep the top and bottom surfaces of the specimens parallel, plates were mounted in the jig shown in Figure 24 for bolt tightening. As shown schematically in Figure 25 , the center plate is forced against the top of the jig and the outside plates are forced against the bottom of the jig. In this way, plates are restrained from rotating relative to each other. It is important to maintain top and bottom surfaces parallel since these will be the loading surfaces for slip load measurements. The jig is also set so that the bolt is near the top of the hole in the outside plates and near the bottom of the hole in the inside plate. This arrangement allows the inside plate to slide through the outside plates during loading without bearing on the bolt. To eliminate any bias in the data due to burr orientation, half of the specimens were constructed with burrs on the outer plates facing away from the center of the specimen and half were constructed with burrs on the outer plates facing toward the center of the specimen.

To determine the slip coefficient from shear tests, it is necessary to know the contact force between the plates. This contact force is equal to the bolt tension. For all installation techniques except the tension control bolts, bolt tension was determined from the load-elongation relationship for the bolts. For the tension control bolts, it was assumed that the

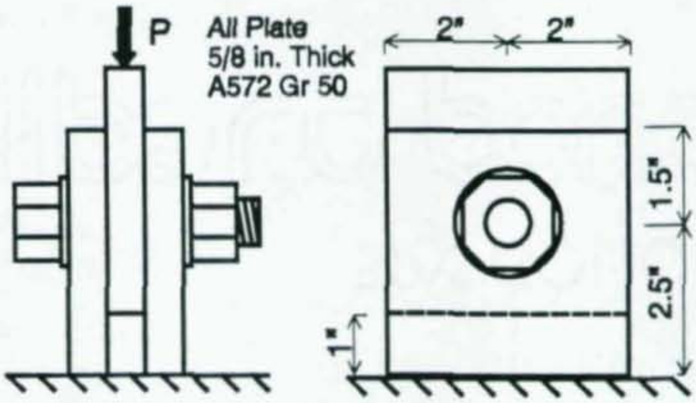

Figure 22. One-Bolt Specimen for Slip Coefficient Tests

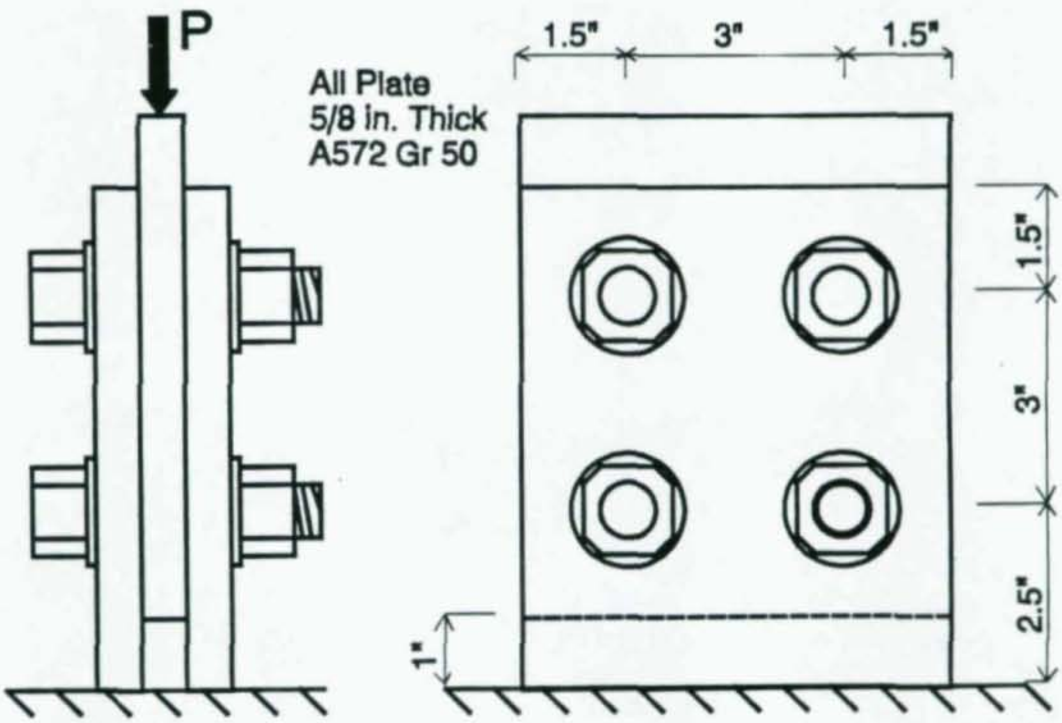

Figure 23. Four-Bolt Specimen for Slip Coefficient Tests

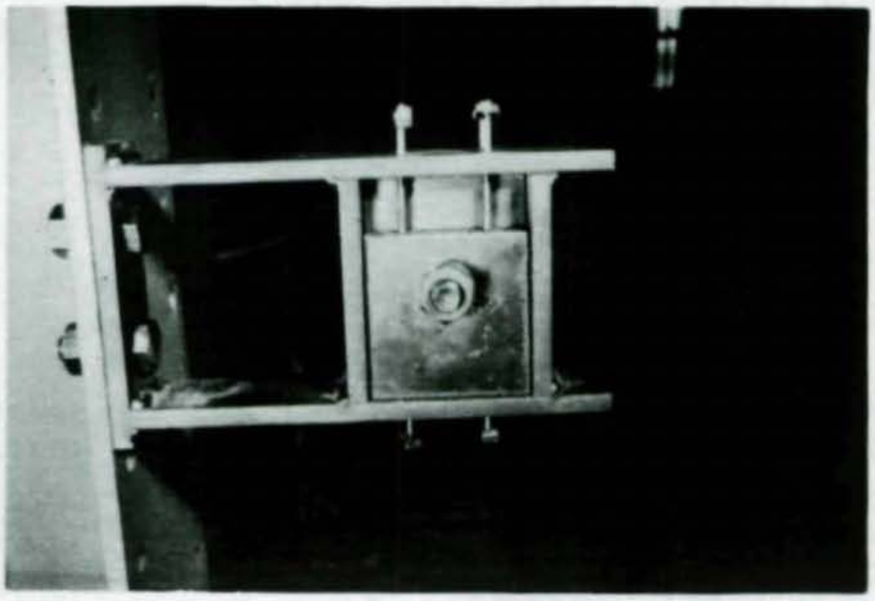

Figure 24. Photograph of Alignment Jig

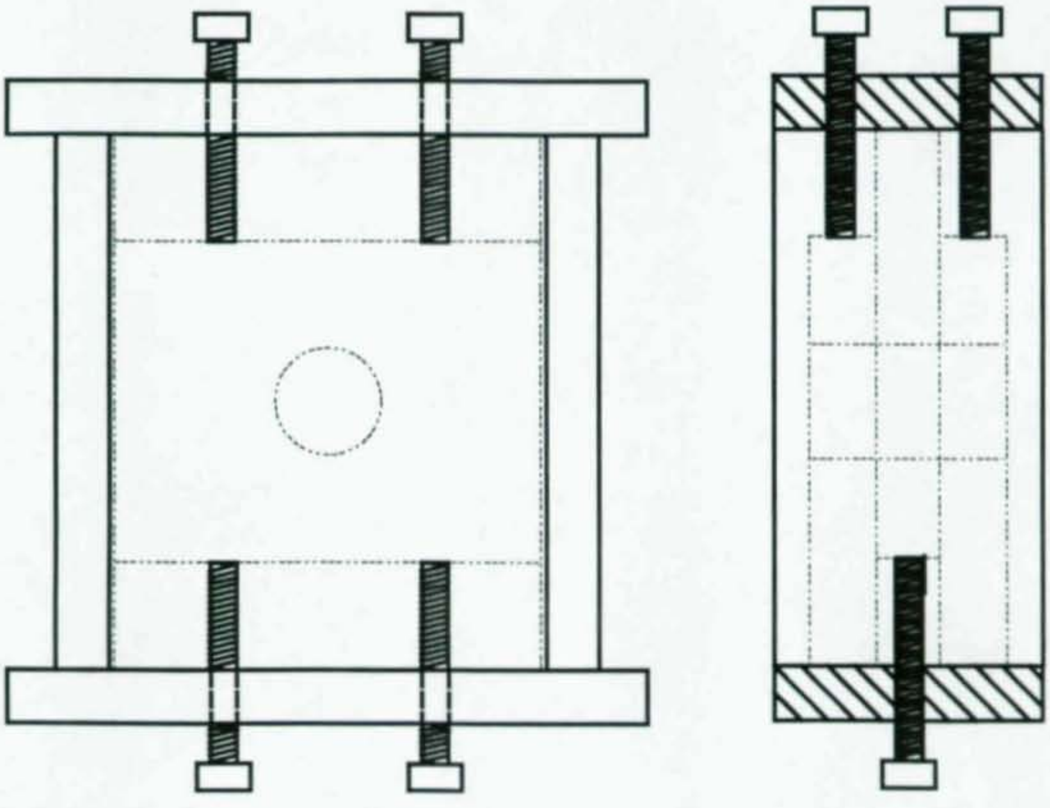

Figure 25. Schematic of Alignment Jig

bolt tension was equal to the average tension measured in the Skidmore-Wilhelm for six bolts taken from the same group of bolts used in the specimens.

The load-elongation relationship for the hex-head bolts is based on measurements made from four bolts tensioned in the Skidmore-Wilhelm. These bolts were of the same diameter, length, grade, and grip as those to be mounted in the specimens. Prior to testing, gage marks were made with a punch on the top and bottom of all bolts. Changes in bolt length during tightening were measured using a 1/10,000-in. dial gage mounted in a frame as shown in Figure 26.

The results of the load-elongation measurements are shown in Figure 27. Data for each of the four bolts are plotted with a different symbol. One second order equation was fit to the initial elastic portion of the data and another was fit to the data above yield. Equations for both curves are given in the figure.

In the test specimen, initial bolt length was measured when the three plates and the bolt had been assembled in the frame and the nut was hand tight. Final length was measured after the bolt had been fully pretensioned according to the installation method used. Actual pretension was determined from the fitted load-elongation curves on the basis of the measured change in length.

5.2 Test Procedure

All one-bolt specimens were tested in a 60-kip capacity universal test machine. All four-bolt specimens were tested in a 300-kip capacity universal test machine. Load was applied at a rate of approximately 10 kips per minute. Deformation was measured using a direct current differential transformer (DCDT) mounted between the loading table and the crosshead. An x-y recorder was used to maintain a continuous record of load versus deformation. A photograph of the apparatus is provided in Figure 28.

Prior to testing, grip was measured at two locations along each vertical edge of the specimen. The two locations were approximately 1.5 in. above and below the center of the bolthole. These measurements were averaged for each specimen and are plotted versus burr height in Figure 29. It can be seen that as burr height increases, there is a slight

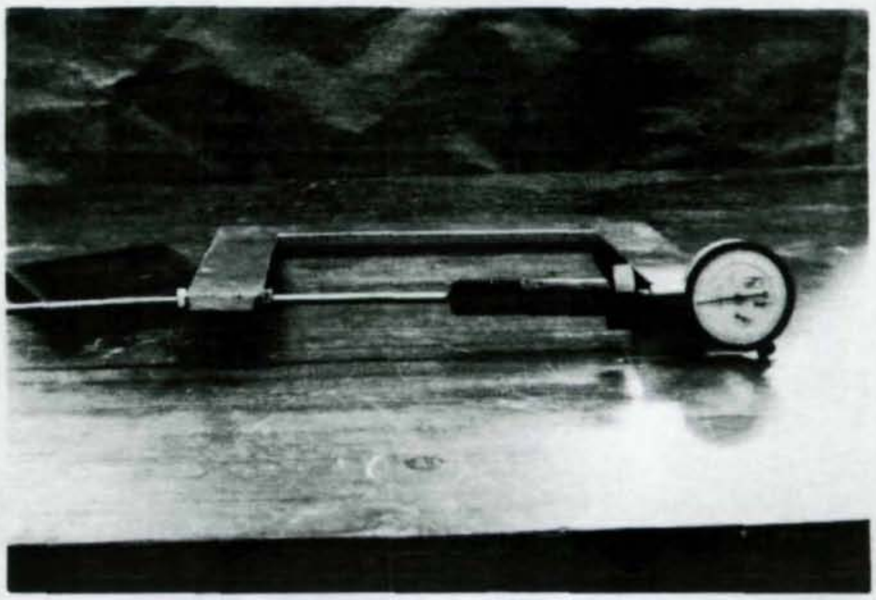

Figure 26. Instrument Used for Bolt Elongation Measurements

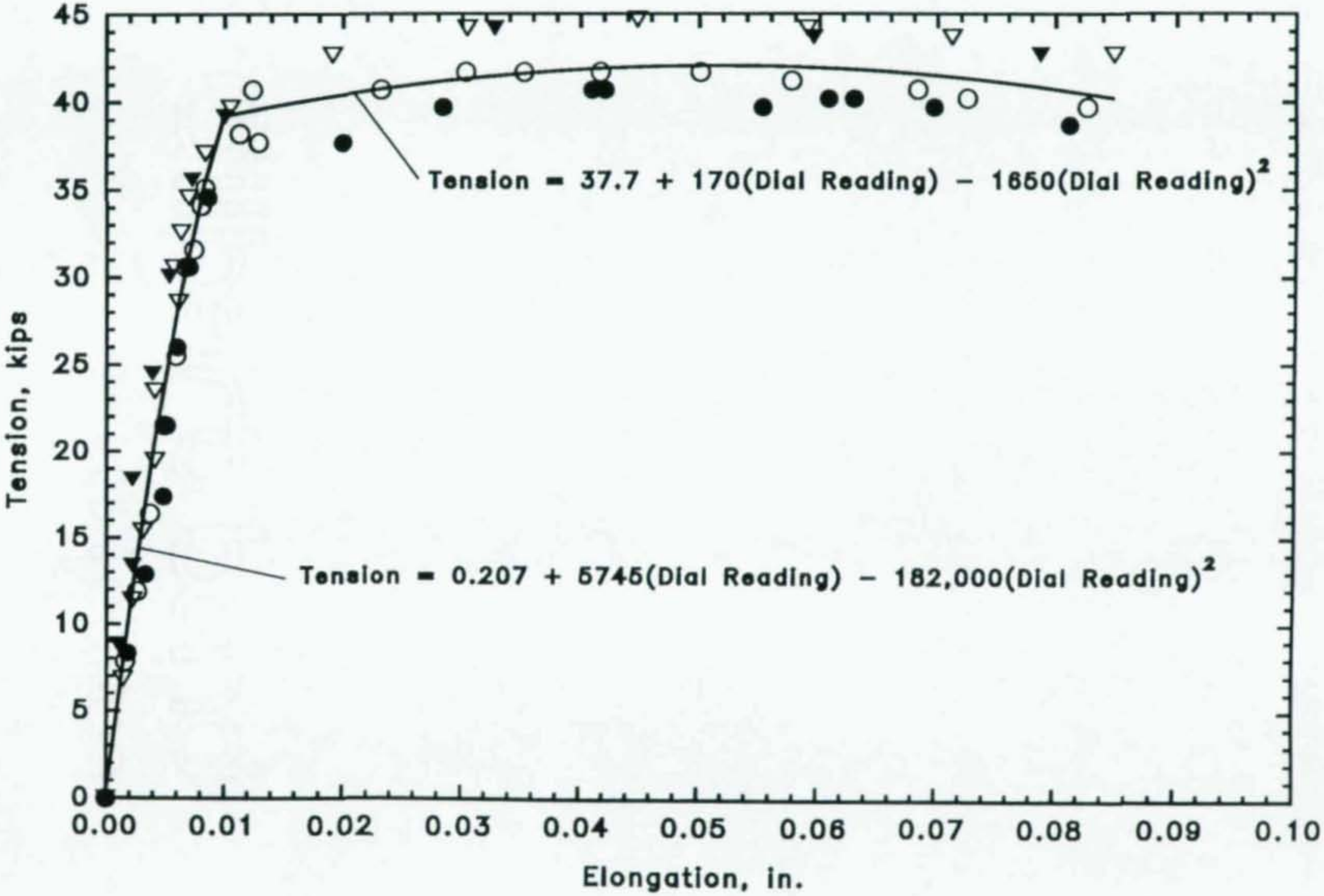

Figure 27. Tension-Elongation Data for Bolts Used in Slip Tests

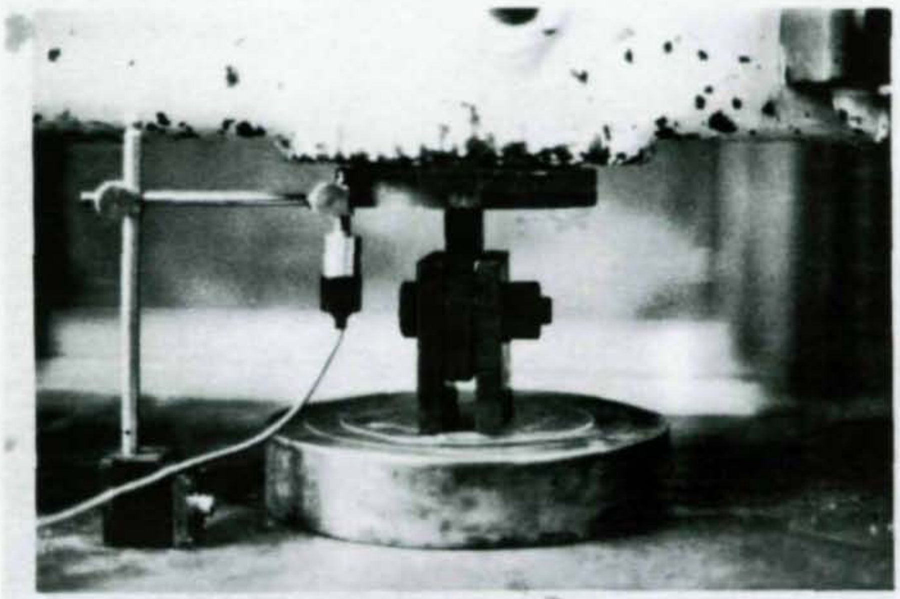

Figure 28. Apparatus for Slip Tests

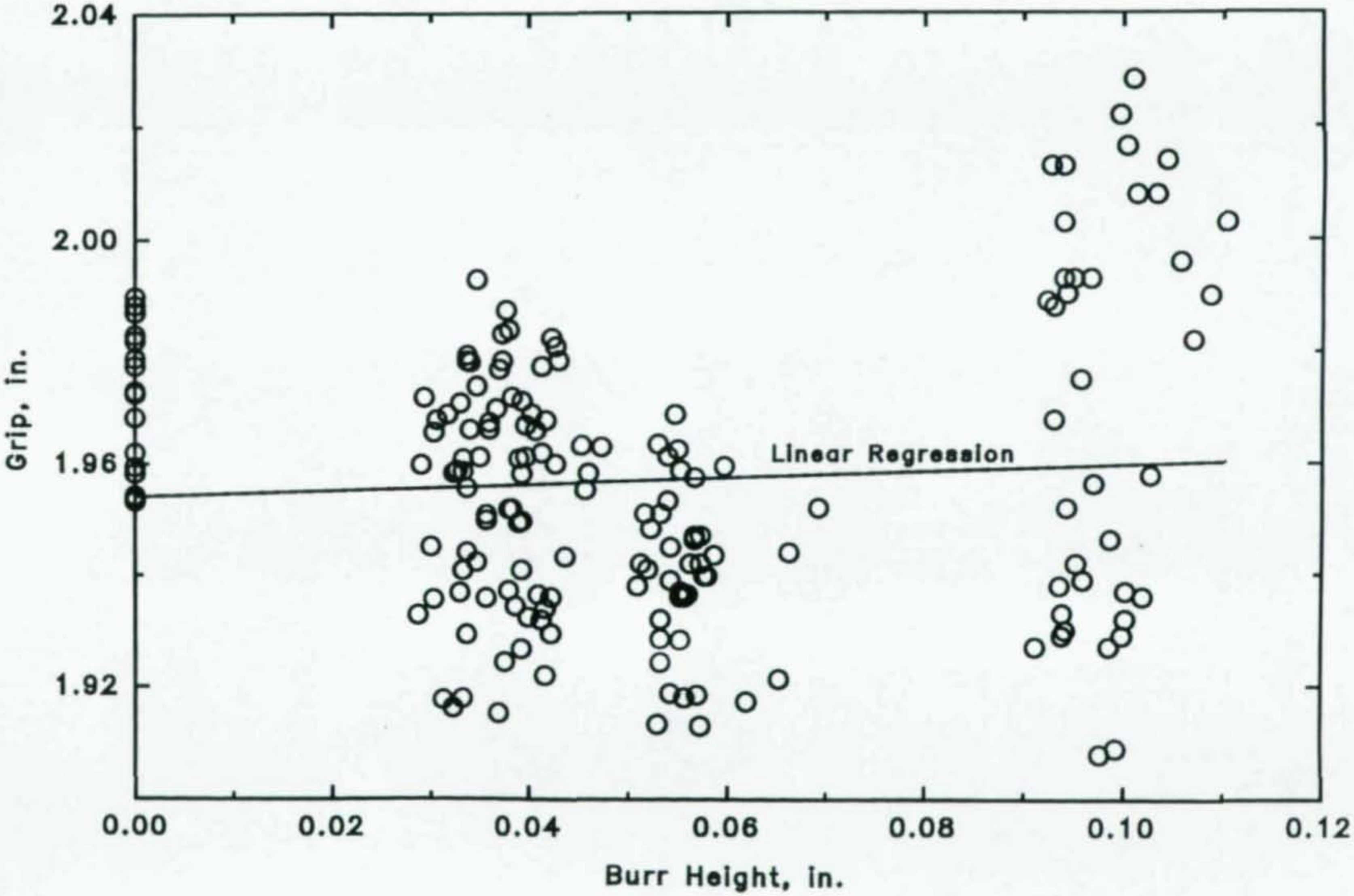

Figure 29. Grip Versus Burr Height for Slip Specimens

tendency for grip to increase. When large burrs are present (approximately 0.10 in.), some specimens exhibit a significant increase in grip.

5.3 Results and Discussion

Plots of load versus deformation for two different specimens are shown in Figures 30 and 31. Note that the deformation scale is set at zero under a load of 500 lbs. Since deformations were measured between the load table and the crosshead, instead of directly on the specimen, this small preload was necessary to eliminate most of the nonlinear behavior associated with seating the specimen. The point of slip is circled and the slip load is written on both plots. In Figure 30, the slip load is easily identified; in Figure 31 the relevant point of slip is not as clear. To establish the point of slip as objectively as possible, slip load was defined as the maximum load prior to any decrease in load with increasing deformation. No minimum limit was set on the amount of decrease in load or increase in deformation.

Slip coefficients were calculated as shown below:

$$k_s = P/(mT)$$

where k_s = slip coefficient, P = slip load, T = bolt tension, and m = number of slip planes. Slip load was taken directly from load-deformation plots, bolt tension was determined on the basis of measured changes in length, and the number of slip planes was always two for these tests.

All slip coefficient versus burr height data are listed in Table 3 and plotted in Figure 32, along with a regression line and the 99% confidence limits for the regression. The first impression this figure generates may be a negative one related to the scatter in the data. To counteract this negative impression, the data are replotted in the form of a histogram in Figure 33. Immediately below, in Figure 34, is a histogram taken from Reference [7]. This reference provides the basis for the RCSC specifications related to slip coefficients. The form of the two histograms is very similar, with the standard deviation of the present data slightly less than that of the data taken from Reference [7]. The mean of the present data is also less than the mean from Reference [7], but is well within the overall bounds of the compiled data.

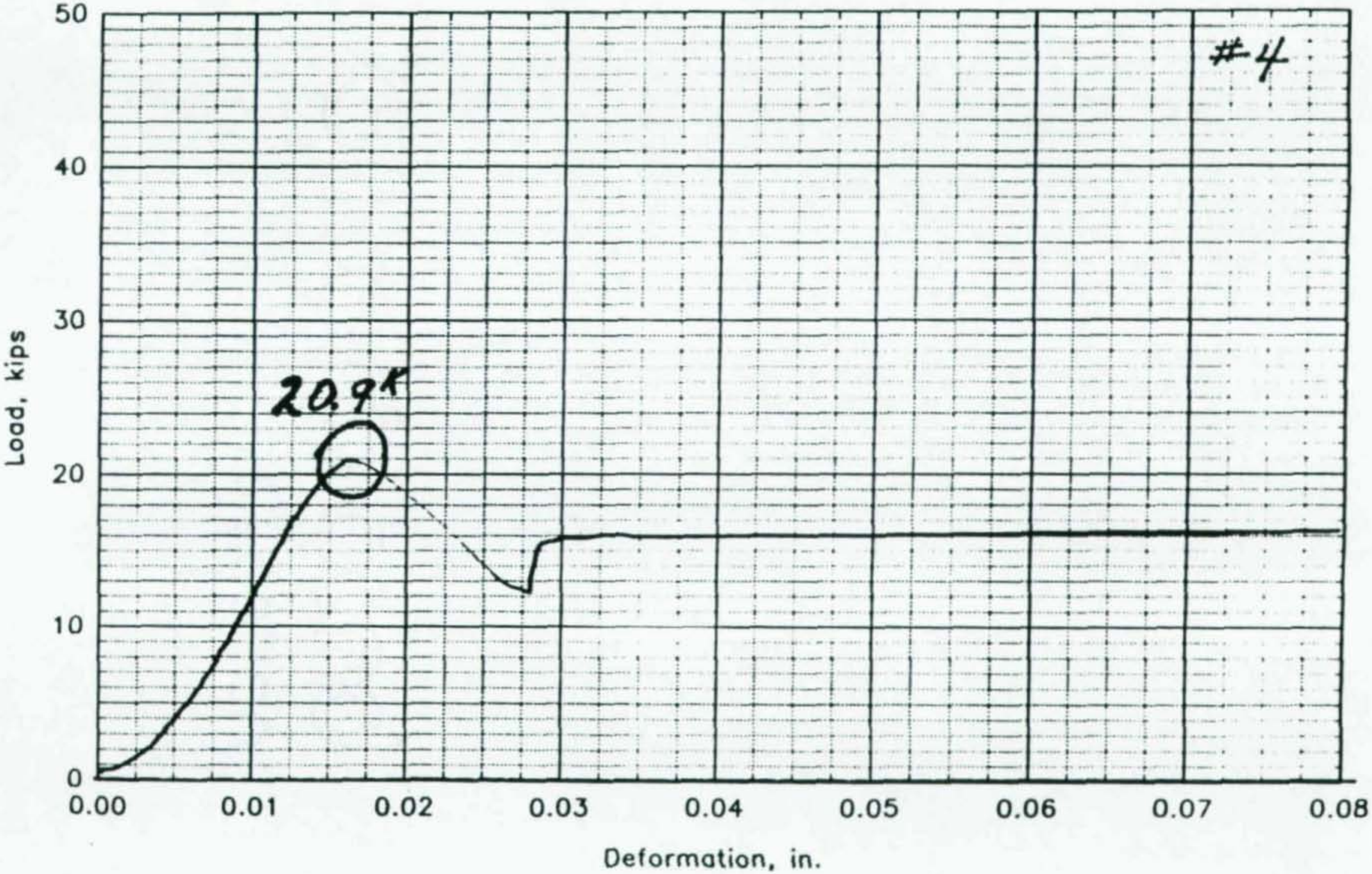

Figure 30. Load Versus Deformation for Specimen 4

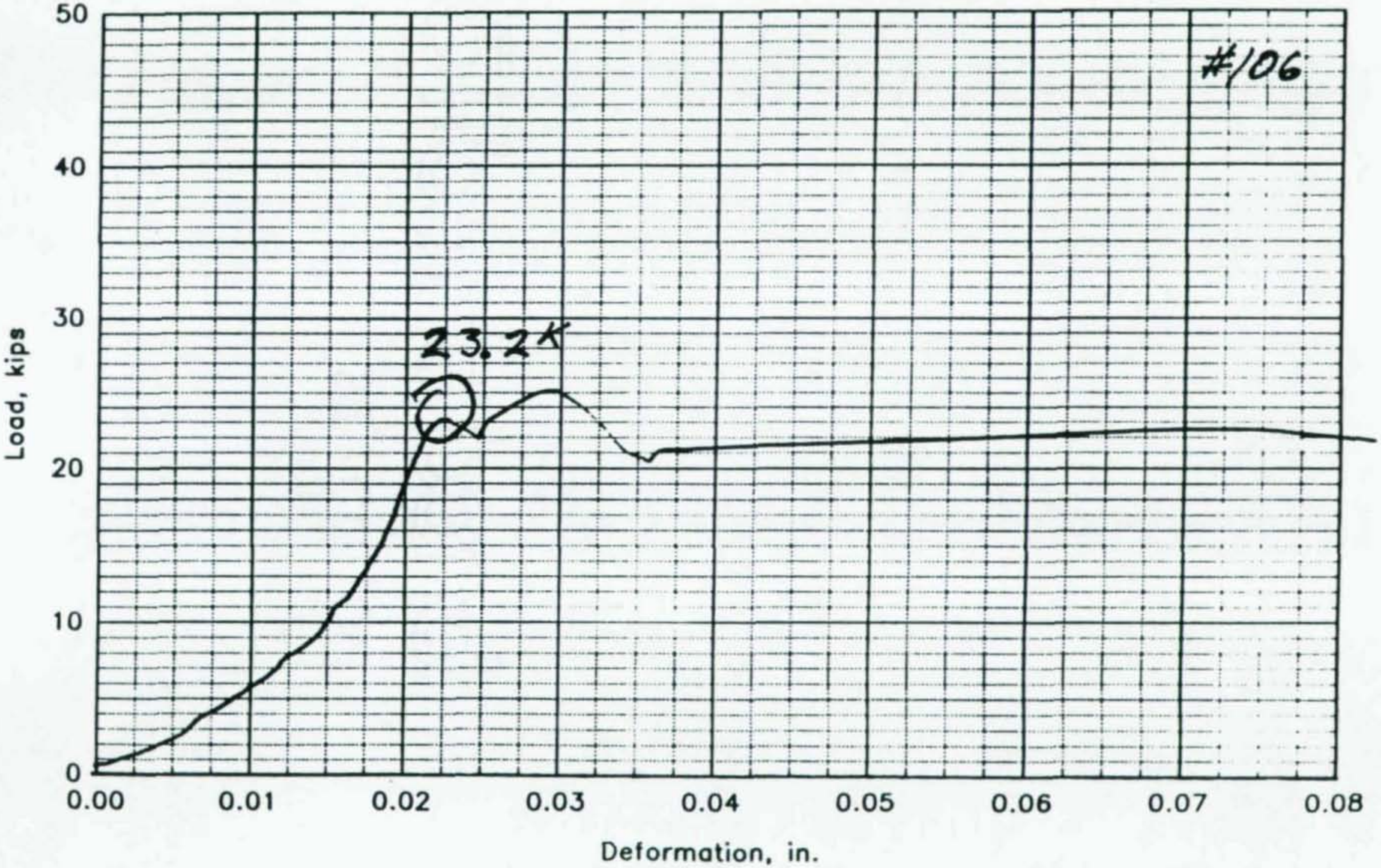

Figure 31. Load Versus Deformation for Specimen 106

TABLE 3. SHEAR CAPACITY IN FRICTION CONNECTIONS

Specimen Number	Bolt Tension, kips	Slip Load kips	Slip Coeffi-cient	Burr Height, in.
1	41.25	17.9	0.217	0.0000
2	41.12	20.2	0.246	0.0000
3	41.22	16.9	0.205	0.0000
4	41.41	20.9	0.252	0.0000
5	41.26	20.7	0.251	0.0000
6	32.90	17.2	0.261	0.0000
7	32.90	16.3	0.248	0.0000
8	32.90	11.2	0.170	0.0000
9	32.90	14.4	0.219	0.0000
10	32.90	14.1	0.214	0.0000
11	36.64	12.1	0.165	0.0000
12	31.80	13.9	0.219	0.0000
13	26.29	13.9	0.264	0.0000
14	30.18	13.3	0.220	0.0000
15	33.33	11.0	0.165	0.0000
16	33.33	14.3	0.215	0.0000
17	34.21	13.8	0.202	0.0000
18	31.16	15.0	0.241	0.0000
19	33.33	16.2	0.243	0.0000
20	28.81	12.8	0.222	0.0000
21	40.10	17.7	0.221	0.0373
22	39.77	18.3	0.230	0.0293
23	39.49	19.0	0.241	0.0337
24	39.68	21.6	0.272	0.0367
25	39.95	17.5	0.219	0.0397
26	40.94	21.4	0.261	0.0370
27	40.85	20.2	0.247	0.0347
28	40.67	19.5	0.240	0.0347
29	40.76	22.5	0.276	0.0373
30	40.63	23.2	0.286	0.0423
31	32.90	13.6	0.207	0.0393
32	32.90	16.9	0.257	0.0347
33	32.90	16.9	0.257	0.0287
34	32.90	11.9	0.181	0.0380
35	32.90	15.8	0.240	0.0370
36	32.90	13.5	0.205	0.0337
37	32.90	17.1	0.260	0.0383
38	32.90	16.9	0.257	0.0327
39	32.90	16.4	0.249	0.0340
40	32.90	16.9	0.257	0.0377
41	30.51	15.6	0.256	0.0333
42	40.08	14.0	0.175	0.0340
43	34.49	17.4	0.252	0.0306
44	35.86	17.8	0.248	0.0350
45	32.73	18.1	0.277	0.0317
46	33.92	15.5	0.228	0.0290
47	36.64	18.2	0.248	0.0357
48	33.92	16.5	0.243	0.0300
49	36.64	18.9	0.258	0.0323

TABLE 3. (Continued)

Specimen Number	Bolt Tension, kips	Slip Load kips	Slip Coeffi-cient	Burr Height, in.
50	31.48	16.8	0.267	0.0303
51	30.18	14.4	0.239	0.0333
52	34.21	15.3	0.224	0.0323
53	31.48	13.9	0.221	0.0333
54	32.11	14.0	0.218	0.0337
55	28.46	13.5	0.237	0.0400
56	32.42	15.4	0.237	0.0330
57	29.50	13.1	0.222	0.0357
58	31.16	17.2	0.276	0.0337
59	28.46	17.9	0.314	0.0313
60	27.75	17.4	0.313	0.0333
61	28.11	18.6	0.331	0.0417
62	29.16	15.5	0.266	0.0390
63	22.77	17.2	0.378	0.0410
64	21.95	16.8	0.383	0.0407
65	20.27	17.6	0.434	0.0453
66	26.66	23.6	0.443	0.0413
67	34.49	22.7	0.329	0.0423
68	31.16	22.9	0.367	0.0390
69	31.48	25.0	0.397	0.0423
70	24.76	23.4	0.473	0.0393
71	32.90	16.4	0.249	0.0417
72	32.90	16.0	0.243	0.0387
73	32.90	17.4	0.264	0.0393
74	32.90	17.4	0.264	0.0303
75	32.90	19.8	0.301	0.0357
76	32.90	20.8	0.316	0.0427
77	32.90	17.4	0.264	0.0393
78	32.90	20.8	0.316	0.0430
79	32.90	21.5	0.327	0.0517
80	32.90	18.8	0.286	0.0473
81	35.32	18.7	0.265	0.0457
82	32.42	17.2	0.265	0.0427
83	33.03	17.0	0.257	0.0437
84	29.16	16.0	0.274	0.0383
85	30.84	14.9	0.242	0.0403
86	36.38	24.0	0.330	0.0390
87	33.92	20.3	0.299	0.0417
88	31.80	22.1	0.347	0.0393
89	37.38	22.6	0.302	0.0397
90	33.63	20.6	0.306	0.0380
91	28.81	16.1	0.279	0.0393
92	34.49	8.8	0.128	0.0360
93	31.80	16.7	0.263	0.0330
94	33.63	18.0	0.268	0.0460
95	28.11	14.3	0.254	0.0413
96	30.18	23.1	0.383	0.0376
97	33.33	22.0	0.330	0.0413

TABLE 3. (Continued)

Specimen Number	Bolt Tension, kips	Slip Load kips	Slip Coeffi-cient	Burr Height, in.
98	35.05	22.9	0.327	0.0380
99	34.49	24.3	0.352	0.0337
100	33.92	22.3	0.329	0.0360
101	32.11	15.5	0.241	0.0553
102	31.80	15.9	0.250	0.0557
103	23.58	14.7	0.312	0.0550
104	29.16	13.0	0.223	0.0530
105	36.64	18.4	0.251	0.0543
106	35.32	23.2	0.328	0.0543
107	37.14	14.3	0.193	0.0567
108	39.30	27.0	0.343	0.0573
109	39.26	22.5	0.287	0.0587
110	39.20	23.2	0.296	0.0520
111	32.90	16.0	0.243	0.0523
112	32.90	17.0	0.258	0.0573
113	32.90	17.2	0.261	0.0510
114	32.90	16.9	0.257	0.0533
115	32.90	8.8	0.134	0.0513
116	32.90	20.8	0.316	0.0540
117	32.90	19.0	0.289	0.0567
118	32.90	13.1	0.199	0.0567
119	32.90	20.5	0.312	0.0560
120	32.90	21.8	0.331	0.0553
121	29.84	19.9	0.333	0.0543
122	31.80	19.8	0.311	0.0563
123	37.38	19.7	0.264	0.0553
124	33.92	16.4	0.242	0.0547
125	33.33	18.9	0.284	0.0540
126	32.73	15.9	0.243	0.0530
127	38.99	15.8	0.203	0.0533
128	38.32	17.7	0.231	0.0557
129	30.51	16.3	0.267	0.0570
130	34.77	18.7	0.269	0.0533
131	30.51	22.3	0.365	0.0553
132	37.38	24.4	0.326	0.0663
133	38.32	23.4	0.305	0.0693
134	30.51	22.6	0.370	0.0577
135	32.73	20.3	0.310	0.0597
136	35.05	14.1	0.201	0.0620
137	36.38	17.9	0.246	0.0533
138	34.21	16.6	0.243	0.0573
139	36.12	20.0	0.277	0.0653
140	33.03	15.8	0.239	0.0580
141	31.80	14.0	0.220	0.0983
142	32.42	19.7	0.304	0.1010
143	34.77	20.9	0.301	0.1003
144	33.33	16.5	0.248	0.0967
145	33.92	18.8	0.277	0.0943
146	30.18	12.0	0.199	0.0930

TABLE 3. (Continued)

Specimen Number	Bolt Tension, kips	Slip Load kips	Slip Coeffi-cient	Burr Height, in.
147	28.81	10.7	0.186	0.0987
148	26.29	10.8	0.205	0.1020
149	27.75	10.4	0.187	0.0953
150	25.91	10.0	0.193	0.0970
151	32.90	18.5	0.281	0.0940
152	32.90	19.2	0.292	0.1103
153	32.90	14.0	0.213	0.1043
154	32.90	10.8	0.164	0.1070
155	32.90	16.5	0.251	0.0997
156	32.90	12.8	0.195	0.1003
157	32.90	13.9	0.211	0.0940
158	32.90	13.2	0.201	0.0913
159	32.90	15.6	0.237	0.0993
160	32.90	16.1	0.245	0.1000
161	31.25	16.4	0.262	0.0940
162	29.16	14.9	0.255	0.1033
163	26.29	14.3	0.272	0.0930
164	31.80	20.0	0.314	0.1087
165	35.86	20.0	0.279	0.1013
166	39.25	17.6	0.224	0.1003
167	35.59	17.5	0.246	0.0960
168	34.77	12.1	0.174	0.1027
169	31.80	11.3	0.178	0.0987
170	32.11	12.5	0.195	0.0940
171	32.11	21.2	0.330	0.0927
172	36.38	20.5	0.282	0.0923
173	34.21	18.0	0.263	0.0957
174	33.92	17.2	0.254	0.0950
175	34.21	19.0	0.278	0.0940
176	36.64	16.0	0.218	0.0937
177	28.11	12.5	0.222	0.0943
178	33.92	19.0	0.280	0.1057
179	39.23	16.6	0.212	0.0943
180	38.77	15.3	0.197	0.0977

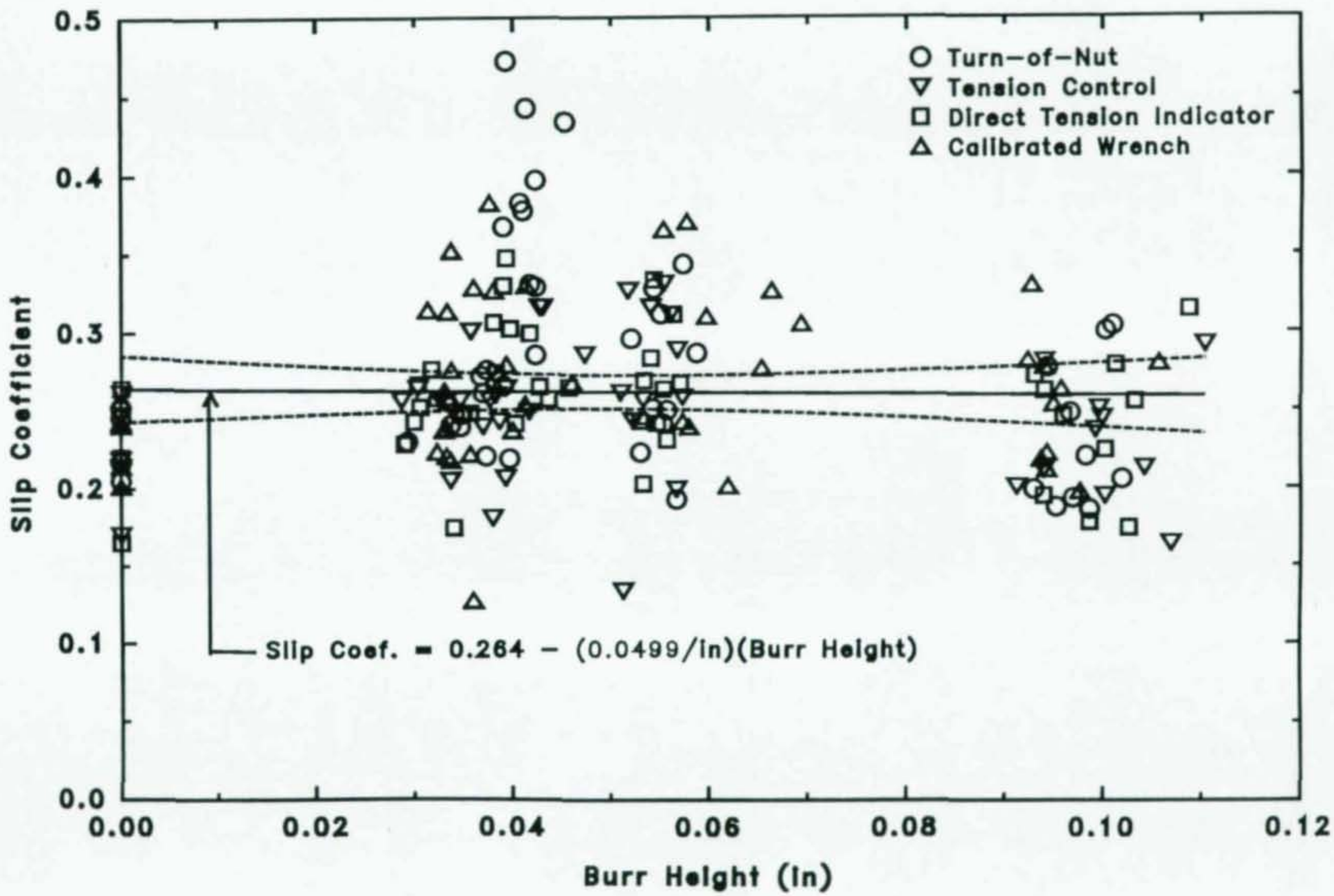

Figure 32. Slip Coefficient Versus Burr Height for All Specimens

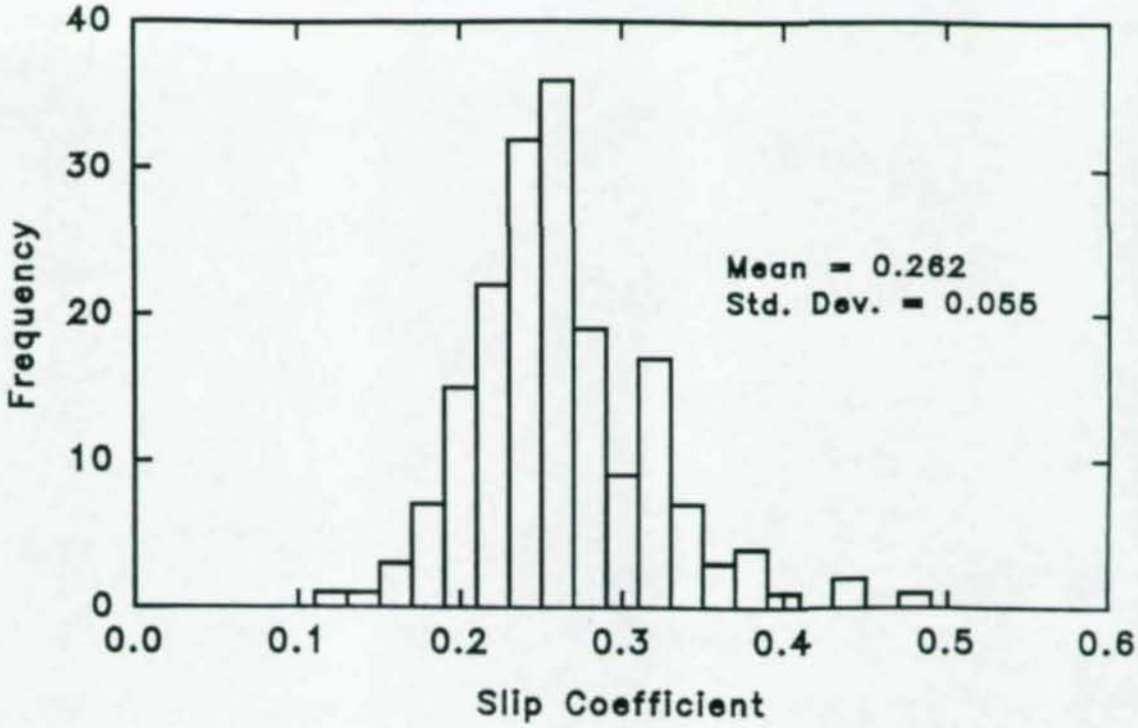

Figure 33. Slip Coefficient Histogram for Current Data

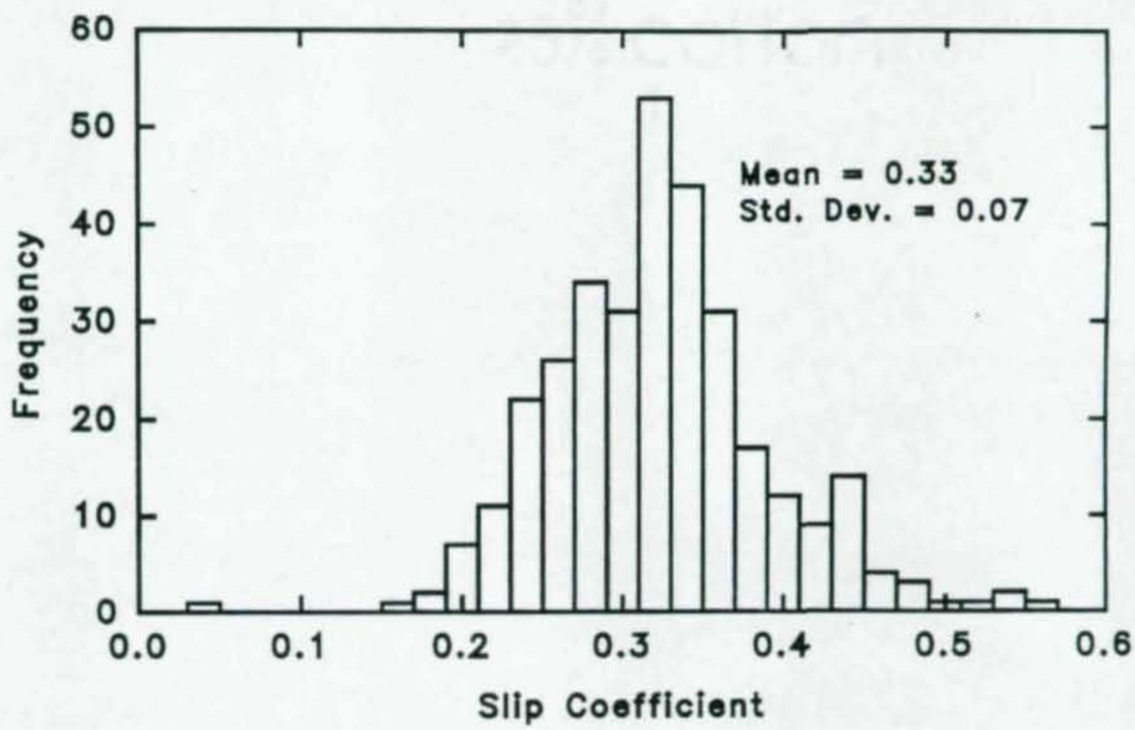

Figure 34. Slip Coefficient Histogram From Reference [7]

also less than the mean from Reference [7], but is well within the overall bounds of the compiled data.

In Figure 35 the data from Figure 32 are replotted with a second order regression line. It can be seen that the slip coefficient first increases with increasing burr height up to a burr height in the 0.05- to 0.06-in. range and then decreases toward burr heights of approximately 0.10 in. Referring to Figure 29, it can be seen that grip size is not significantly affected for burrs smaller than 0.06 in., indicating that contact between plate surfaces is not significantly affected. Plates with small burrs benefit from interlocking of the burrs under pretension pressure without sacrificing overall surface contact. When burrs are very large, the benefit from burr interlock is still present, but a substantial amount of overall surface contact is lost.

In Figures 36 through 39 the data are grouped according to method of tightening. The lightweight regression line and confidence limits shown on these figures are based on all slip coefficient data and are identical to those shown on Figure 32. The heavyweight regression line is a second order fit to the individual sets of data. The individual data sets demonstrate the same variation in slip coefficient with burr height as the data taken as a whole. Slip coefficient is not adversely affected for burrs smaller than 1/16 in., regardless of the tightening method used.

The fact that the slip coefficient is not adversely affected by burrs smaller than 1/16 in. does not mean the strength of the connection is unaffected. The connection strength is a function of both slip coefficient and contact pressure between plate surfaces. This contact pressure is produced by bolt tension; in the previous chapter it was shown that bolt tension is strongly affected by burrs when turn-of-nut tightening is used and weakly affected when the calibrated wrench is used. Connection strength can be reduced due to a lower bolt pretension than expected, even if the slip coefficient is adequate. This conclusion is essentially in agreement with the work of Polyzois and Yura [10], who reported that connection strength is not adversely affected by burrs as long as the proper bolt tension is achieved.

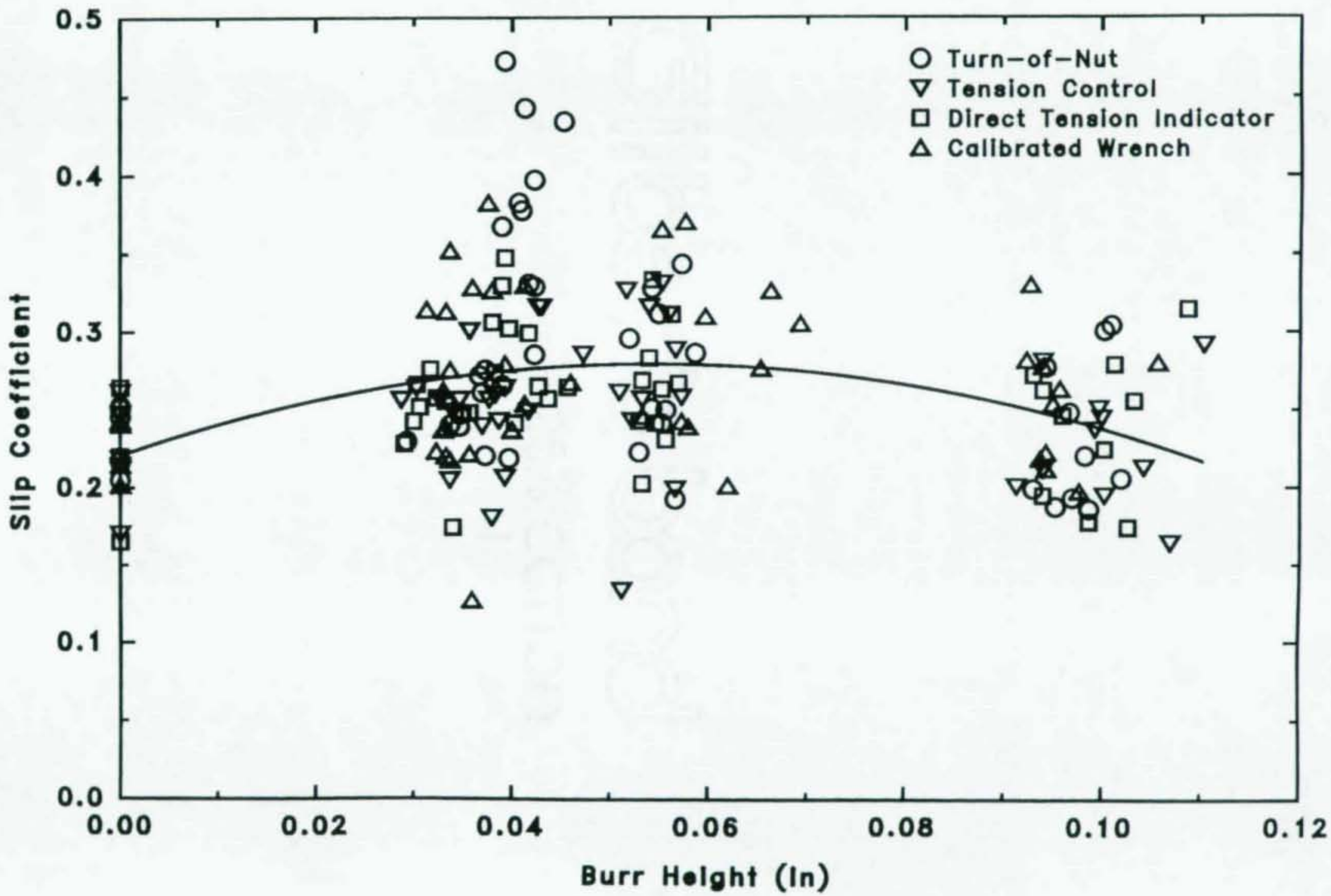

Figure 35. Slip Coefficients for All Specimens With a Second Order Regression Line

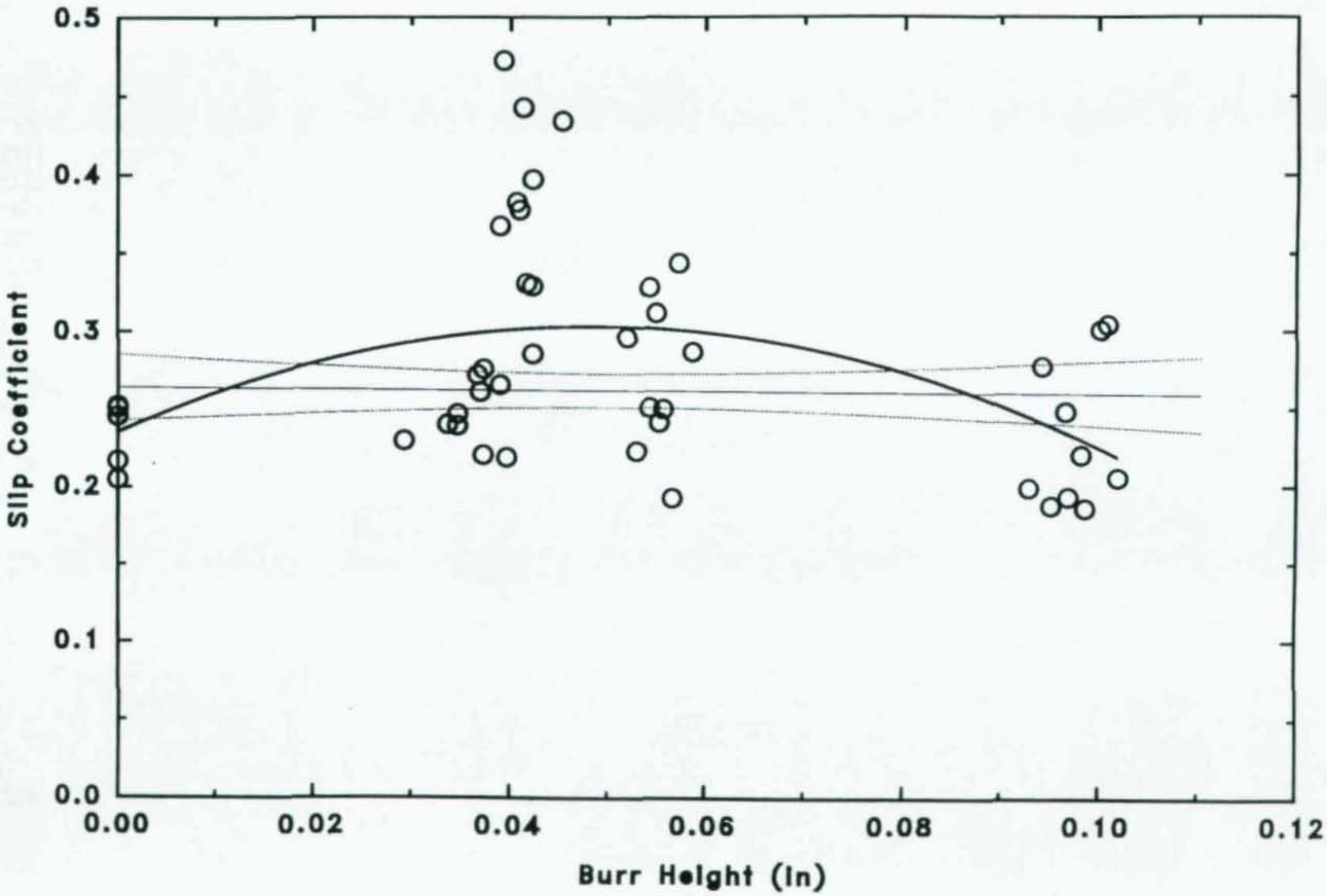

Figure 36. Slip Coefficients for Turn-of-Nut Tightening

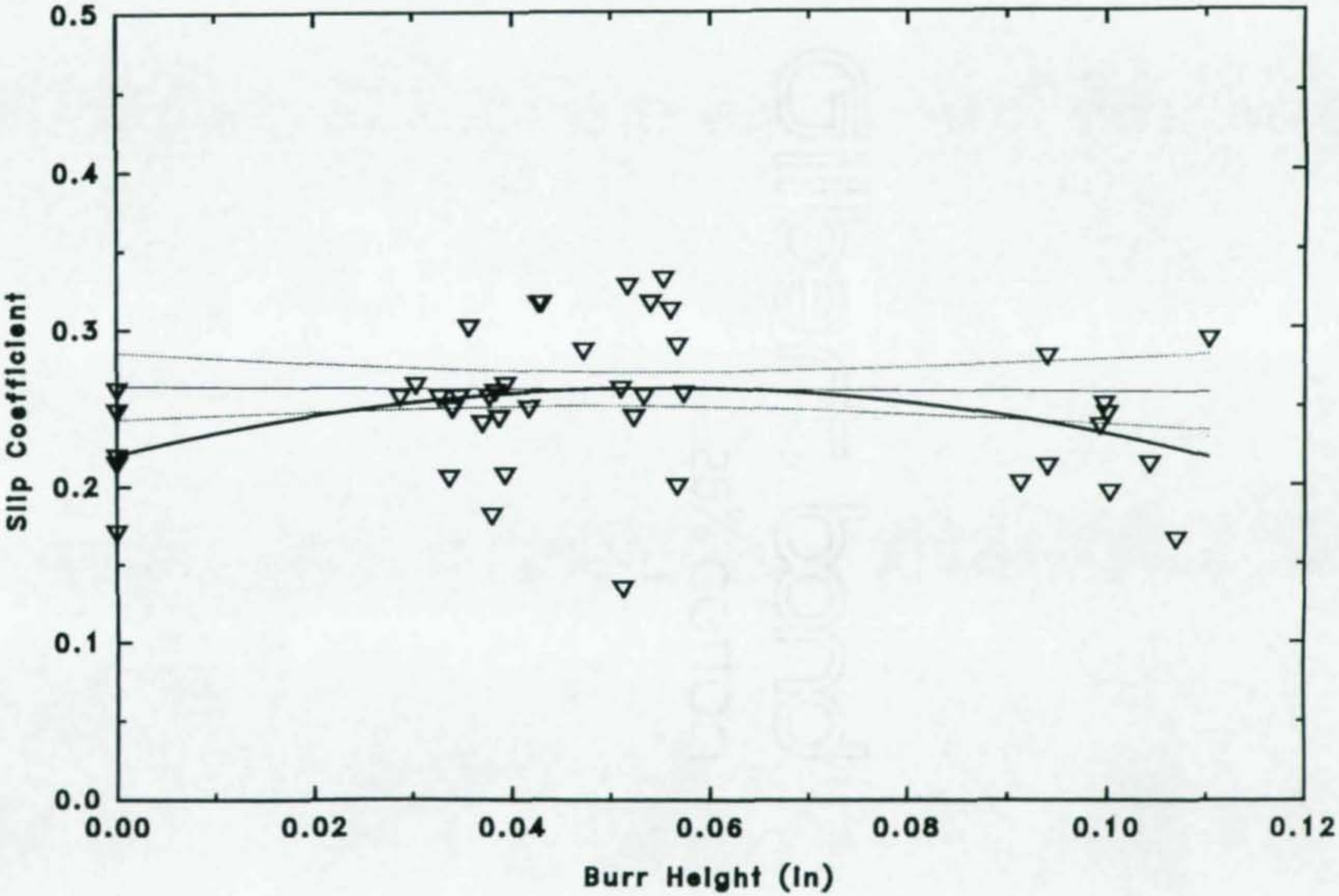

Figure 37. Slip Coefficients for Tension Control Tightening

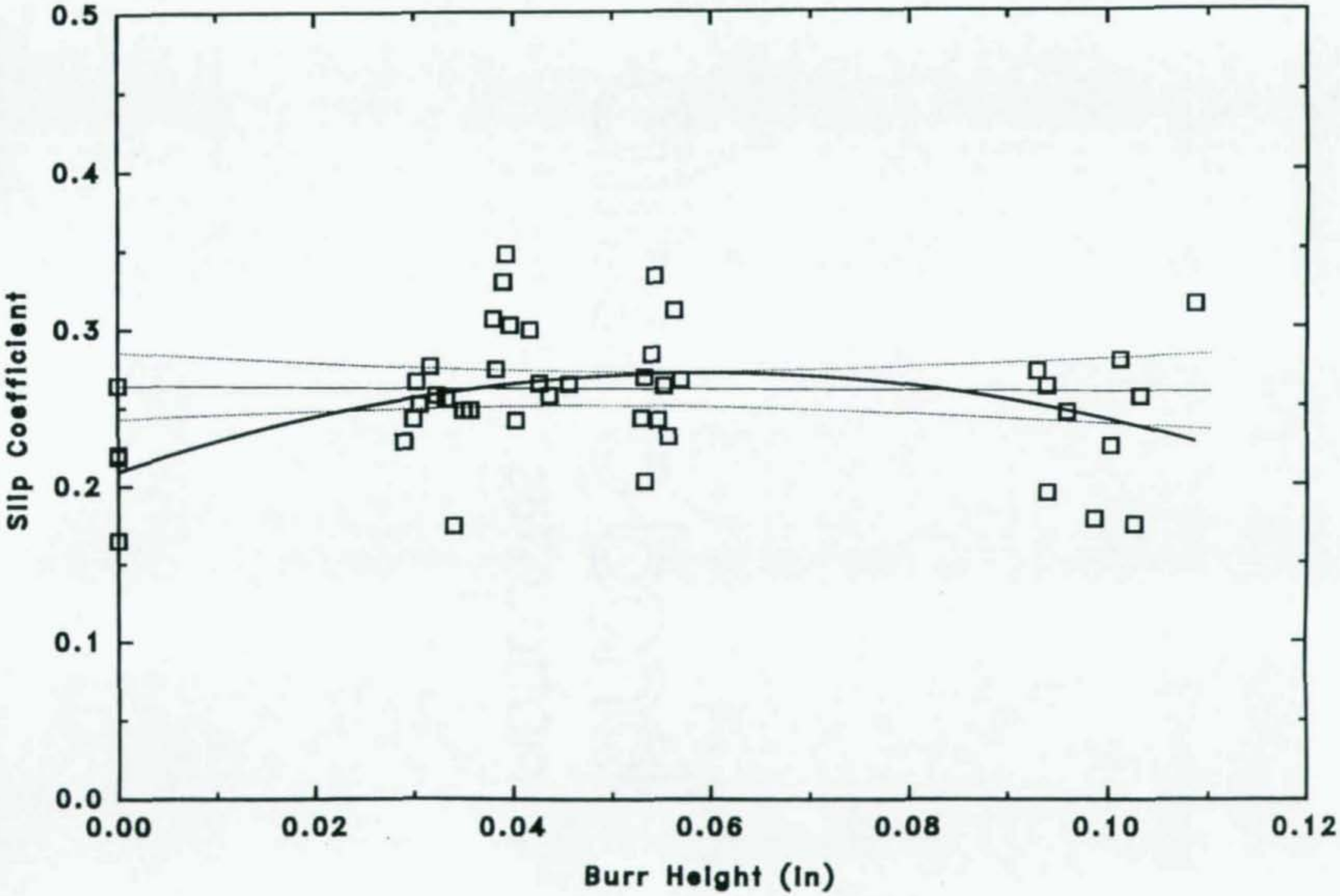

Figure 38. Slip Coefficients for Direct Tension Indicator Tightening

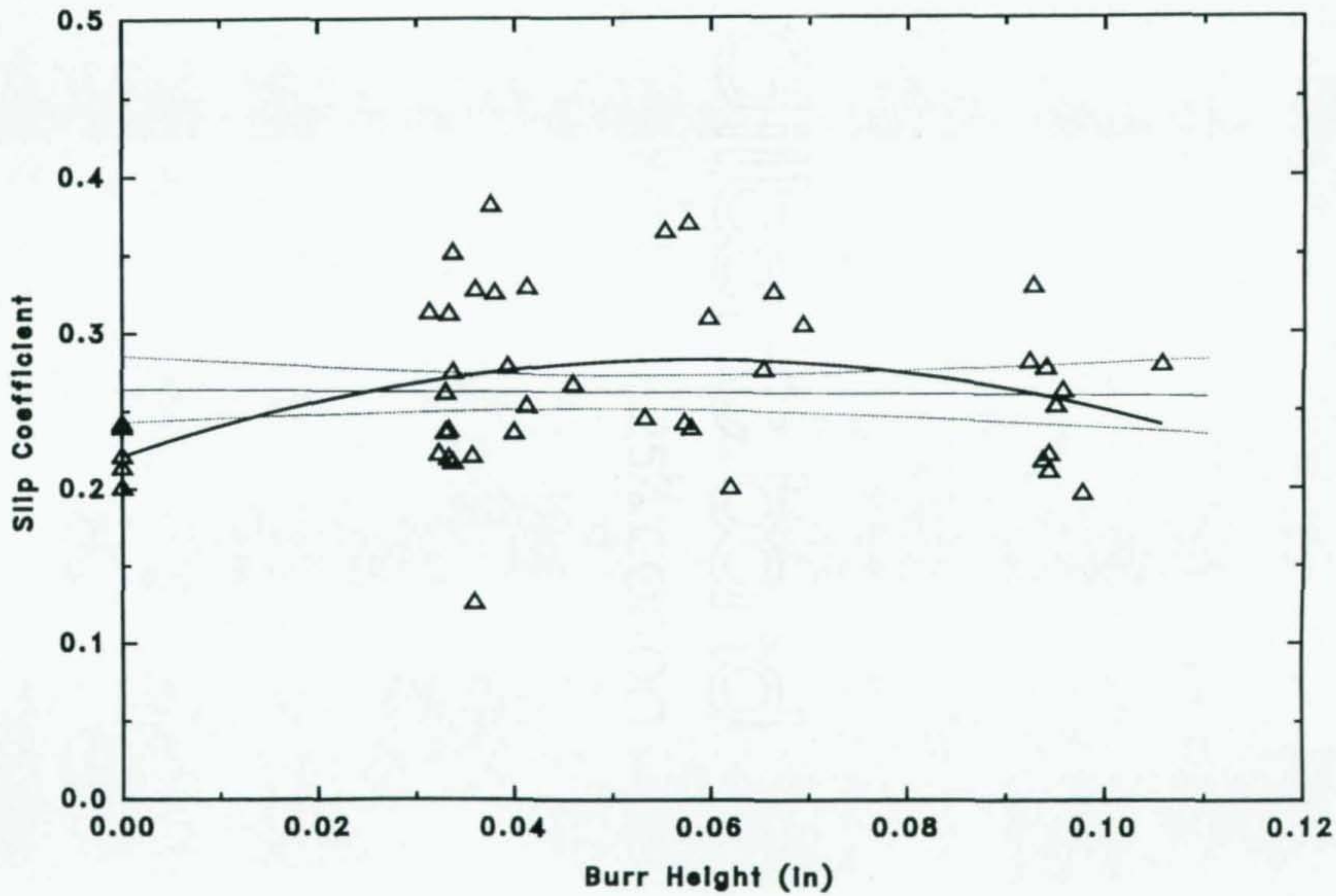

Figure 39. Slip Coefficients for Calibrated Wrench Tightening

In recognition of the importance of bolt tension to connection strength, bolt tension versus burr height was subjected to further study using slip coefficient specimens. Data are plotted for direct tension indicator specimens in Figure 40 and for calibrated wrench specimens in Figure 41. Bolt tensions were determined on the basis of measured changes in bolt length. In these figures, these new data are compared to data previously reported in Chapter 4. Tension control bolts are not included in this set of figures because bolt tension could not be determined independently by measuring change in bolt length. Turn-of-nut bolts are not included in this study because nuts were rotated from 180 to 360° past snug (depending on burr height) in order to achieve a tension near that required by the RCSC specification.

The data shown in Figure 40 again demonstrate that use of direct tension indicators results in consistent bolt tensions, regardless of burr height. The new data for the calibrated wrench display a trend opposite to that seen in Chapter 4. There is a slight increase in bolt tension with burr height. The reason for this difference is not clear. It may be related to the bolthead restraint in the Skidmore-Wilhelm, to the much larger grip for the specimens with bolts passing first through the Skidmore-Wilhelm and then through the three plates making up the specimens, or to a difference in stiffness between the Skidmore-Wilhelm and the plates [5]. This matter will require additional testing to resolve.

5.4 Pilot Tests

The bulk of the data described in this report are the result of tests on one-bolt connections made with 3/4-in. diameter A325 bolts. Two brief series of tests were conducted to determine the effect of (1) multiple bolts in a connection, and (2) higher bolt strength. Data from these pilot tests will be evaluated in terms of agreement with trends noted from the bulk of the data.

5.4.1 Multiple Bolt Connection

A drawing of the specimen is shown in Figure 23. Specimen preparation and test procedure have been described in Sections 5.1 and 5.2. Only turn-of-nut tightening and tension control bolts were used in this portion of the study. In calculating the slip coefficient,

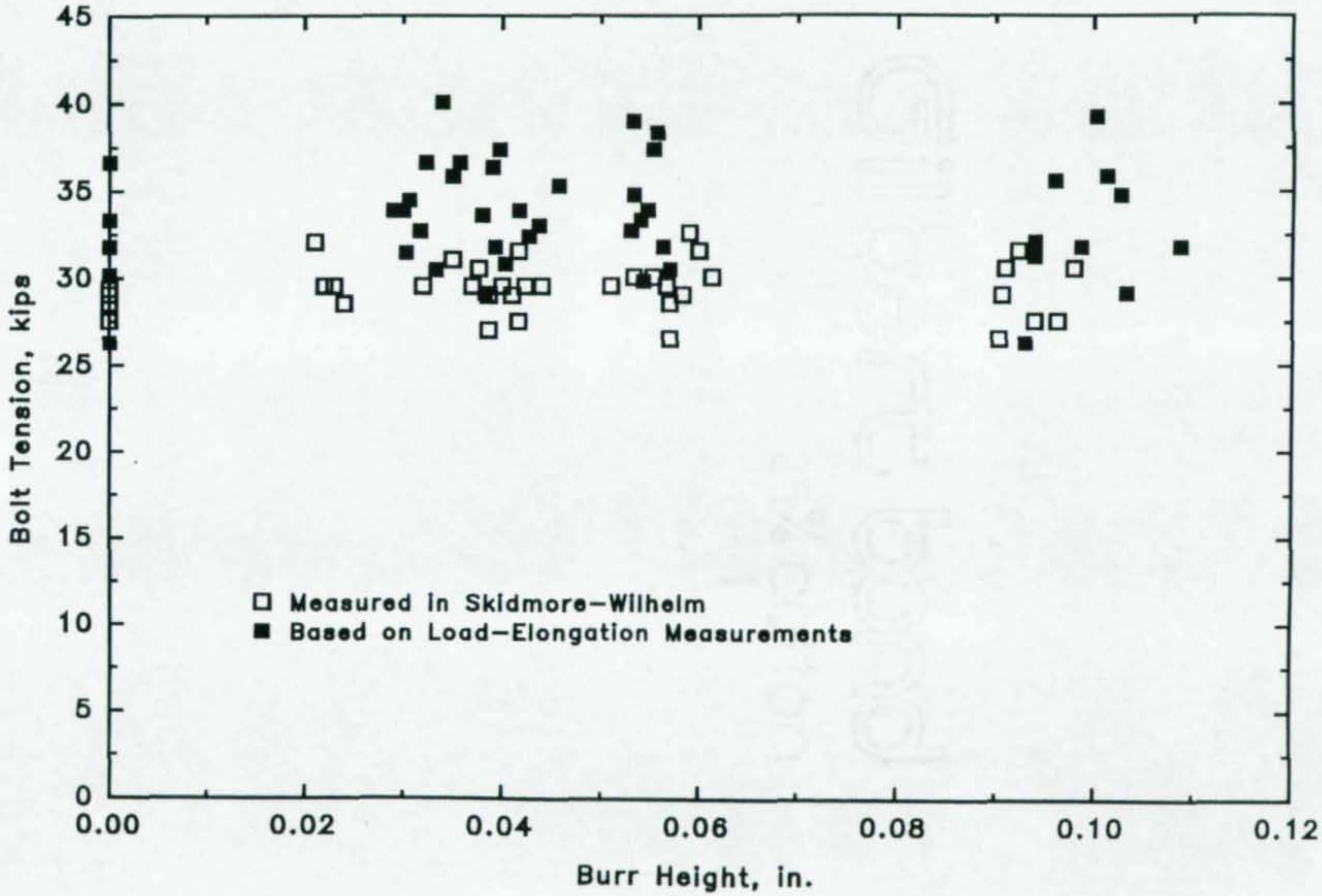

Figure 40. Comparison of Bolt Tension Measured in Skidmore-Wilhelm to Load-Elongation Based Tension for Direct Tension Indicator Tightening

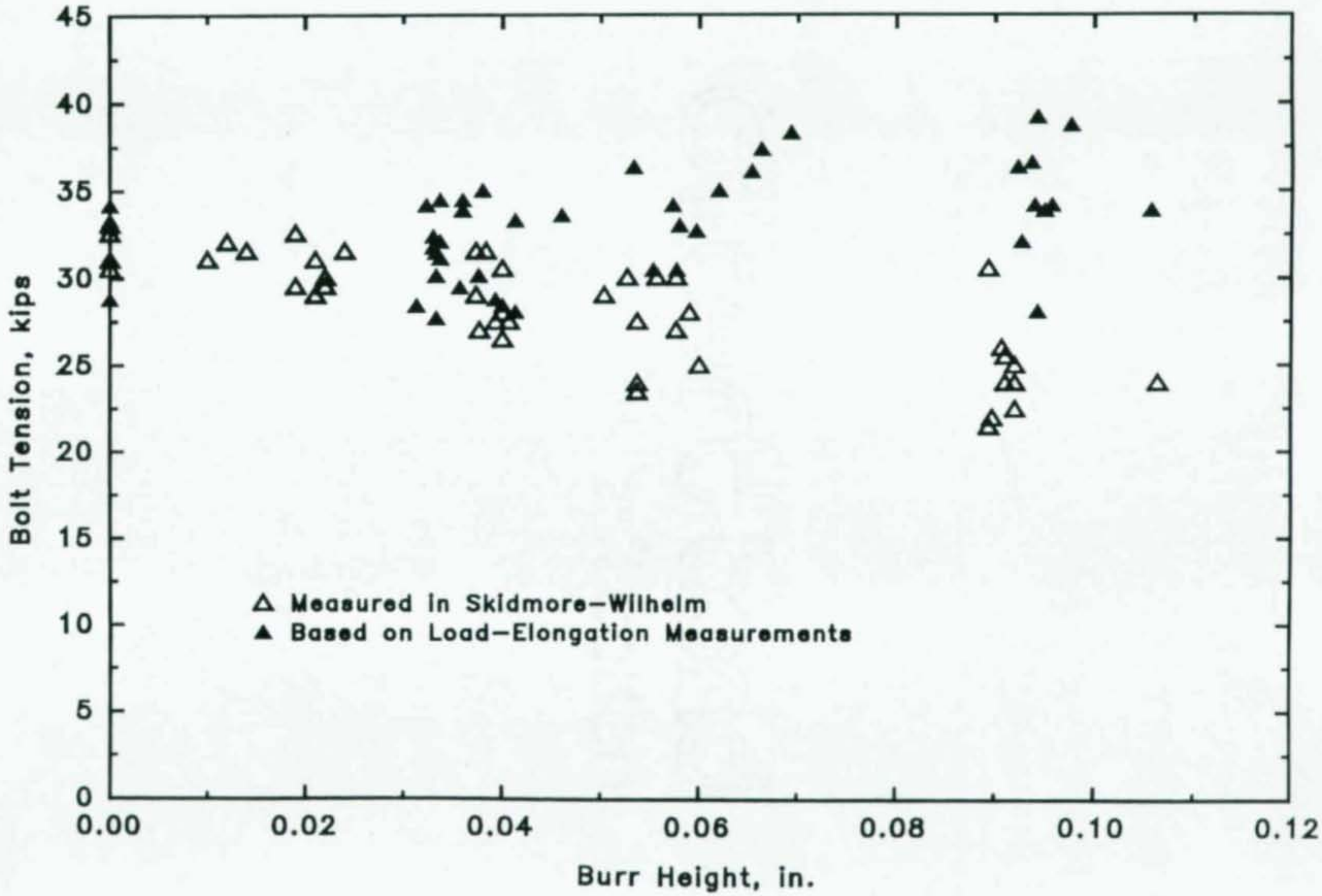

Figure 41. Comparison of Bolt Tension Measured in Skidmore-Wilhelm to Load-Elongation Based Tension for Calibrated Wrench Tightening

bolt tension is taken to be the total tension in the four bolts, slip load is the full force at slip from the load-deformation plot, and number of slip planes is two.

Slip coefficient versus burr height is plotted in Figure 42. As can be seen in the figure, only specimens with burrs removed by grinding and specimens with burrs approximately 0.10 in. in height were tested. The average slip coefficient is approximately 0.22. The regression line has a very slight upward slope. The variation of slip coefficient with burr height appears to be similar to that for the single bolt connections.

Figure 43 is a plot of bolt tension versus burr height for the individual bolts in the four-bolt connections. Only turn-of-nut data are plotted since an independent measure of bolt tension cannot be made for the tension control bolts. The data are separated according to order tightened. All bolts were first snugged and then fully tensioned, in the same order. When burr height is 0 in., bolt tension is not dependent on order of tightening. When large burrs are present, the first and second bolts tightened carried much less tension than the third and fourth bolts tightened. Apparently, tightening of the third and fourth bolts further compressed the burrs under the first and second bolts and relieved some of the tension in these bolts. Similar behavior has been observed by Oswald et al. [9] in field tests with large-diameter A490 bolts. The result is a lower connection slip capacity.

Referring to Figure 42, notice that the tension control data tend to plot below the turn-of-nut data. This behavior is explained by the fact that the tension used in slip coefficient calculations for turn-of-nut bolts resulted from measurements on the specific bolts in the connection, while tension in tension control bolts was assumed to be the same as that measured earlier in the Skidmore-Wilhelm. The drop in tension due to burr compression could not be accounted for with tension control bolts.

The presence of large burrs in multiple bolt connections results in low bolt tension in the first bolts tightened, regardless of the tightening method used. This low bolt tension leads to a reduced connection capacity. The effect of burrs of intermediate height cannot be evaluated from the available data.

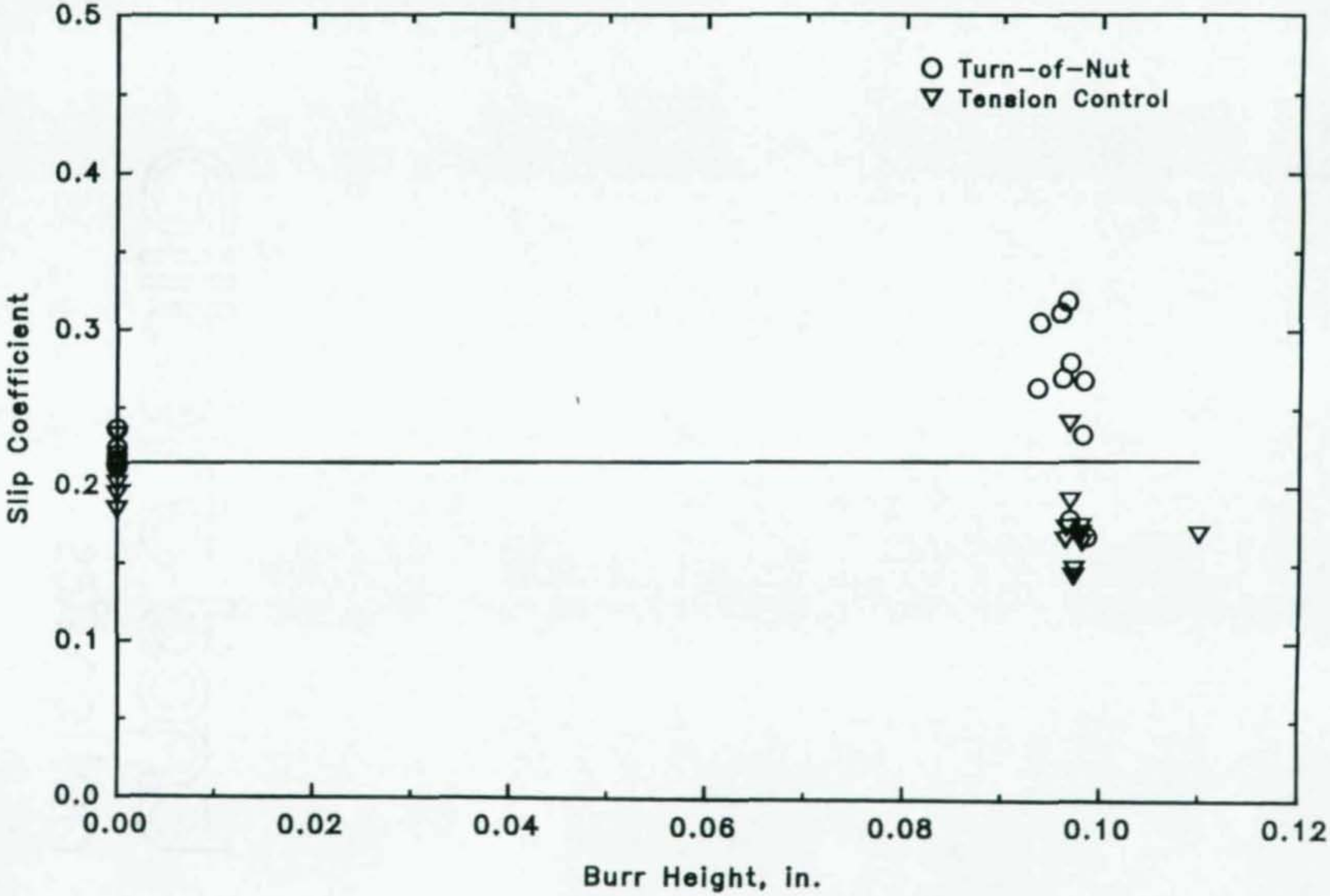

Figure 42. Slip Coefficients for Four-Bolt Specimens

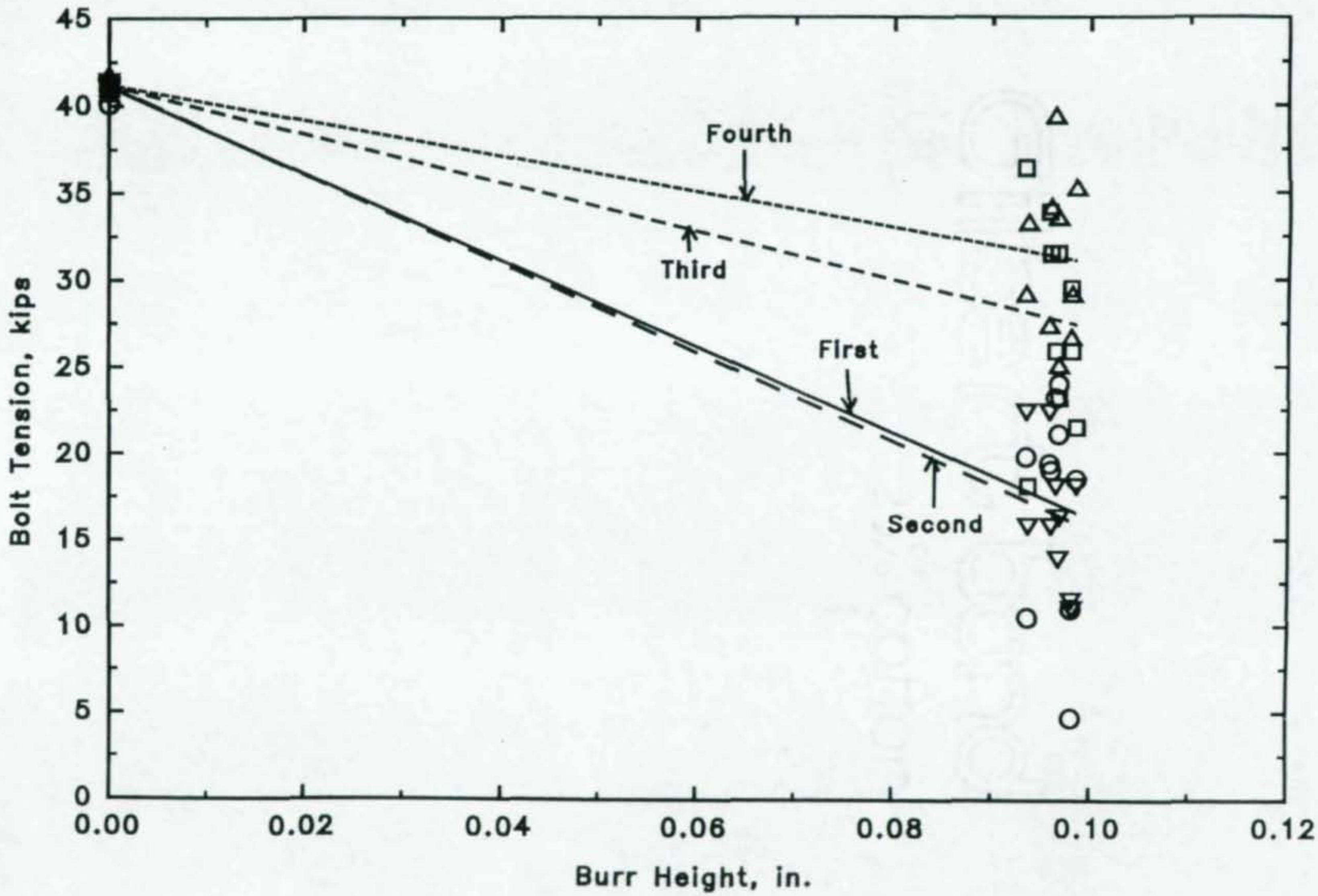

Figure 43. Effect of Tightening Sequence on Bolt Tension

5.4.2 One-Inch Diameter A490

Specimens were prepared and tested in the same manner as specimens with 3/4-in. A325 bolts. Only tension control bolts were used in this portion of the study. This portion of the study was further limited to specimens with burrs removed by grinding and specimens with burrs approximately 1/8 in. in height.

Slip coefficient versus burr height is plotted in Figure 44 along with a regression line. The data indicate that slip coefficient increases with increasing burr height. There are not sufficient data to evaluate the effect of burrs of intermediate height.

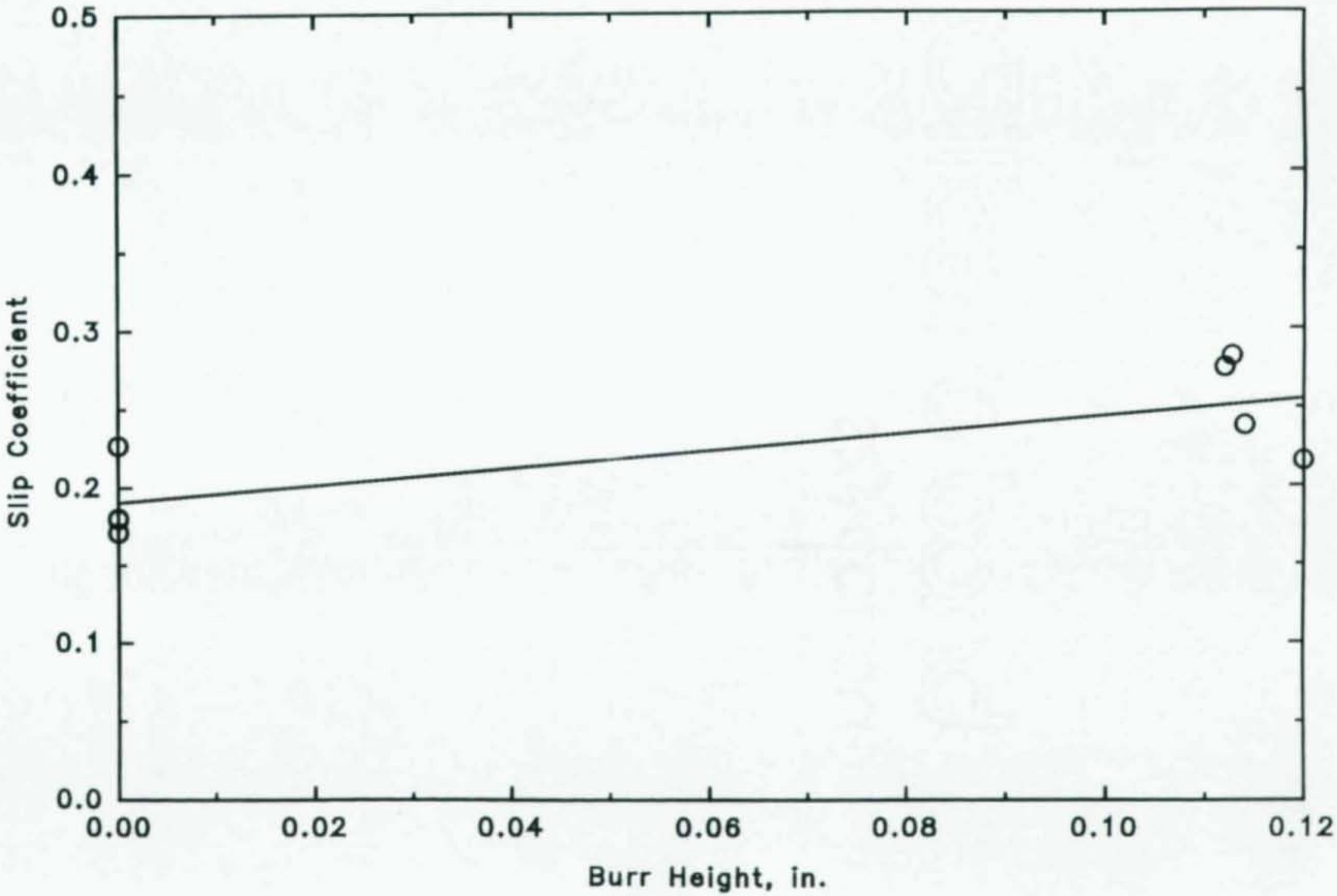

Figure 44. Slip Coefficients for One-Inch Diameter A490 Bolts

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

Tests have been conducted to assess the effect of burrs on the shear capacity of bolted connections. Both bearing and slip-critical connections were tested. The majority of the connections were constructed with single, 3/4-in. diameter A325 bolts, but pilot studies were undertaken with a four-bolt connection and with 1-in. diameter A490 bolts. All specimens were constructed using A572 Grade 50 steel plate.

In bearing connections, bolts were loaded in double shear in a tension-type specimen. Nuts were turned finger tight only. Failure of the connection was always the result of exceeding the ultimate shear capacity of the bolt. The theoretical shear plane was always on the unthreaded portion of the bolt, but the large burrs sometimes caused the faying surface of one outside plate to fall on the threaded portion.

Bolts in slip-critical connections were tightened using turn-of-nut, tension control wrench, direct tension indicator, and calibrated wrench methods. Roughly half of the tests on slip-critical connections were conducted to determine the effect of burrs on bolt tension; the other half were conducted to determine the effect on the slip coefficient. All faying surfaces were clean mill scale.

6.2 Conclusions

On the basis of the research described in this report, the following conclusions are drawn:

1. There is a slight decrease in bolt ultimate shear capacity with increasing burr height. The decrease is insignificant for burr heights of 1/16 in. or less.
2. If burrs are present in a connection, bolt tension cannot be reliably achieved using turn-of-nut or calibrated wrench methods. Tension control bolts and direct tension indicator methods can be used to reliably achieve bolt tension in single bolt connections, even when burrs up to 1/10 in. are present.

3. Slip coefficients tend to increase slightly as burr height increases from 0 in. to approximately 1/16 in. Beyond 1/16 in., slip coefficients slowly decrease with increasing burr height.
4. Pilot tests conducted on specimens constructed with 1-in. diameter A490 bolts provided results very similar to those obtained with 3/4-in. A325 bolts. Bolt strength does not appear to affect the relationship between slip coefficient and burr height.
5. Pilot tests conducted on multiple bolt specimens indicate that slip coefficient is not affected by multiple bolts. However, bolt tension is seriously degraded when large burrs (approximately 1/10 in. in height) are present in a multiple bolt connection.

6.3 Recommendations

The recommendations listed below are based on the assumption that no further tests are to be conducted. If additional tests (as described in Section 6.4 below) are performed, consideration of Recommendation 1 should be postponed pending the outcome of those tests.

1. In Section 3(b) of the RCSC Specification, the sentence "Burrs that would prevent solid seating of the connected parts in the snug tight condition shall be removed" should be replaced by "Burrs shall be removed from the connected parts if the connection is slip-critical. If the connection is not slip-critical, burrs extending 1/16 in. or less above the plate surface are permitted."
2. In Section 8(c) of the RCSC Specification, the sentence "The snug tight condition is defined as the tightness that exists when all plies in a joint are in firm contact" should be deleted. This recommendation is supported by the Commentary to Section 8(c) of the RCSC Specification.
3. The literature search conducted as a part of this research revealed a conflict between past research recommendations and specifications in regard to oversize holes. Past reports should be re-examined and this conflict should be resolved.

6.4 Additional Research Needs

1. Pilot tests conducted as a part of this research reveal a need for tests on multiple bolt, slip-critical connections with burr heights between 0 and 1/8 in. The presence of burrs 1/8 in. in height caused a substantial reduction in bolt tension for the first bolts tightened. Smaller burrs are expected to cause a smaller reduction. Tests are required to determine if this reduction is significant. This problem might also be solved by incremental tightening of the bolts. Further work is needed to satisfactorily resolve these questions.
2. The literature search conducted as a part of this project discovered some uncertainties with regard to filler plates. Additional tests with filler plates of varying thicknesses and main plates of varying yield strengths are needed to address these uncertainties.

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