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LARGE BOLTED CONNECTIONS

THE EFFECT OF OVERSIZE AND SLOTTED HOLES ON THE BEHAVIOR OF A BOLTED JOINT

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ABSTRACT

Twenty-one bolted joints were tested to determine the effect of oversize holes and slotted holes on the slip behavior and ultimate strength of bolted joints. Hole sizes studied had standard, 1/4-in. and 5/16-in. clearances. Slots placed both parallel and transverse to the line of load were studied. All joints were of A36 steel plate fastened by 1-in. A325 bolts. Also studied were the need for washers for oversize holes and changes in bolt tension. For holes with 1/4-in. clearance there was no decrease in the slip coefficient, excessive loss in bolt tension or inadequate preload. The studies indicated that a washer is desirable under the turned element to prevent severe galling. A decrease in the slip coefficient was observed for the joints with 5/16-in. hole clearance and for the joints with slotted holes. Slotted holes placed perpendicular to the line of load did not decrease the ultimate strength of the joints.

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1. INTRODUCTION

The current (1966) Specifications for Structural Joints using ASTM A325 or A490 Bolts, as approved by the Research Council on Riveted and Bolted Structural Joints recognizes two types of shear connections, designated as friction-type and bearing-type, respectively.[1]

In a friction-type joint, movement of the connected parts is not tolerated because of the detrimental effects on the behavior of the structure. For this type joint slip constitutes failure, and working loads must be resisted by friction between the connected parts with a reasonable factor of safety against the occurrence of slip.

Where slip of the bolted joint would not be objectionable, a bearing-type connection can be used. For this type of joint, the working loads may be resisted by bearing of the bolts against the sides of the holes. In such a connection it is the shearing of the bolts or failure of the connected parts that constitutes failure and allowable stresses are based on the ultimate strength of the connection.

Behavior of Bolted Joints

In bolted joints with clean mill scale faying surfaces, working load is resisted by frictional forces acting on the faying surfaces of the connected material. The value of the maximum frictional force is related directly to the normal force and the condition of the contact surfaces. The clamping force of the bolts provides the normal force in a bolted connection.

When load is applied to a bolted joint, higher frictional forces exist at the ends of the plates in the joint than in the middle of the joint because of the strain compatibility condition.[2] At one end of the joint the main plate is carrying a relatively higher load than the adjacent lap plates. This condition eventually causes a relative displacement of the faying surfaces near the ends of the joint. As the load is increased, these areas extend inward from the ends of the joint. The maximum frictional resistance of the connection occurs when the slip areas cover the entire faying surface. If the load is further increased, a large relative displacement between the plates of the connection occurs, an event known as major slip. The load at which this movement occurs is called the slip load. The relationship between the initial clamping force of the bolts and the load at major slip is known as the slip coefficient.[3] This does not necessarily compare with the "coefficient of friction" values obtained from sliding block tests which involve a more uniformly applied normal force and a rigid body behavior of the adjacent materials.

After slip occurs, the joint load is transmitted by the bearing of the plate against the bolts. Failure occurs either when the bolts shear or when the connected plate fails. The ultimate strength can usually be predicted by knowing the ultimate shear strength of the bolts as determined by shear calibration tests and the ultimate tensile strength of the connected material as determined by coupon calibration tests.

The present specifications specify that the bolts in a bolted connection are to be used in holes not more than 1/16 inch in excess of the bolt diameter. There are no provisions in the specifications for the use of holes any larger than this.

1.1 Purpose

The studies that have been conducted to date on bolted connections have been primarily on holes with a 1/16 inch clearance. There is a need to evaluate the performance of bolted connections with a greater amount of oversize as it frequently occurs because of reaming and mis-matching.

Slotted holes are also often necessary when a new steel structure is connected to an existing structure.[4] Both oversize and slotted holes are desirable to permit erection adjustments. The purpose of this study was to evaluate the effect oversize and slotted holes have on the slip resistance and ultimate strength of bolted joints. The results of this study would be useful to determine whether joints with oversize or slotted holes could function satisfactorily as friction-type or bearing-type connections. This information could provide useful guidance in the use of specifications.

1.2 Scope

The study was primarily concerned with the effect oversize and slotted holes have on:

(1) losses in bolt tension after installation,

(2) the slip resistance of a joint,

(3) the ability to tighten bolts using the standard installation technique

(4) whether washers are needed for oversize holes; and

(5) the changes in bolt tension during testing.

The effect of slotted holes placed perpendicular to the line of loading on the ultimate strength of a joint was also observed.

The testing program consisted of twenty-one bolted joints. Fifteen were designed as friction-type joints and six were designed as bearing-type joints. Twelve of the friction-type joints were oversize hole specimens with hole clearances ranging from 1/16-in., (the present maximum allowable clearance) to 5/16-in., five times the present maximum allowable clearance. The remaining three friction-type joints had slotted holes in the enclosed plies with the slots placed parallel to the direction of load. The six specimens designed as bearing-type joints had slots placed perpendicular to the line of loading. The joint geometry was varied to evaluate the effect on joint strength. These joints also provided information on slip resistance.

2. PREVIOUS WORK

Various studies have analyzed the behavior of high strength bolts and bolted joints when the bolts were installed in holes larger than their diameters. Early laboratory and field tests indicated that, among other things, high strength bolts could be installed in holes up to 1/16-in. larger than their diameter without a noticable effect on the performance of the bolts or of the joints.[5] The Research Council on Riveted and Bolted Structural Joints, in their first specification issued in 1951 permitted a bolt hole clearance of 1/16-in.

Hoyer[6] reported in 1959 that studies conducted in Germany indicated that there was no influence on the sliding load for holes up to 1/8-in. larger than the bolt.

Chesson and Munse[7] studied the effects of tightening bolts in holes with up to 1/8-in. clearance using the turn-of-nut method with and without washers under the turned element. They concluded that in the case of oversize holes up to 1/8-in. greater in diameter than the bolt there may be some reduction in bolt tension when washers are omitted and when finished hex head bolts and nuts are used, but the clamping force will still be in excess of the required tension for A325 bolts. (See Fig. 1).

Studies to determine the loss in preload of high strength bolts due to relaxation have generally indicated that the total loss is about

10% of the initial preload. Research that has been conducted in Germany since 1954[8,9] has shown that high strength bolts were observed to lose about 10% of their preload over a two-year period. Also, the preload was unaffected by temperature changes.[10]

In South Africa, Denkhaus[11] observed that the total loss in bolt load using a washer was about 9% after 1 day, and 2% from 1 day to 1 year.

Studies on high tensile bolts in Japan[12] showed bolt relaxations of about 6% after 11 years for bolts tightened to their yield point.

Chesson and Munse[7] also observed the effects of holes with up to 1/8-in. clearance on the relaxation of A325 bolts. They found that there was no significant difference in the amount of bolt tension lost with time for the 1/8-in. clearance holes either with washers or without washers. The loss in bolt tension for all tests was less than 10% over a period of from 1 to 5 days.

Tests conducted by the Lamson and Sessions Company on a load analyzer[13] showed a loss in tension of less than 10% over a period of days.

A study to determine the decrease of the preload in high strength bolts over a period of time was conducted in the Netherlands.[14] It was concluded that the loss would be about 5% over 20 years for a bolt with 2 washers and about 10% over 20 years for a bolt with one washer.

Studies to determine the changes in tension in the bolts of a joint as load was applied were conducted at Lehigh University.[15] The results showed that the bolt tension decreased from 1% to 8% at major slip due to the Poisson effect. Joints with a 4-in. grip showed a decrease in bolt tension after major slip. Nester[16] observed a decrease in bolt tension from 0 to 8.6% at major slip.

There is no record of any research done to date on the effect of slotted holes on the performance of either high strength bolts or of bolted joints.

3. TESTING PROGRAM

3.1 Description of Specimens

All twenty-one test specimens were fabricated from 1-in. thick A36 steel plate supplied from the same heat. They had two lines of 1-in. diameter A325 bolts connecting four plies of plate at a pitch of 5-1/4-in. The faying surfaces were clean mill scale.

Twelve specimens containing holes of varying amounts of oversize and three specimens containing slotted holes were designed as friction-type joints. The geometrical layout of the oversize hole joints is shown in Fig. 2.

The twelve joints with oversize holes were divided into four groups of three joints. The ratio of net plate area to total bolt shear area, (the A_n/A_s ratio) was 0.68.

The first group of three joints, designated OH1, had a hole diameter of 1-1/16-in. providing the maximum allowable hole clearance of 1/16-in. These three joints served as control specimens for the entire test series. Because the holes were normal size, the bolts were installed without washers.

In another phase of this research project, a number of bolted joints were tested to determine the influence of variation of the contact area upon the slip resistance. These specimens were fabricated from the same plate as the specimens being discussed. The faying surface condition for both groups of joints were identical. The joints of the latter series had a single line of four 7/8-in. A325 bolts and the contact area was varied by inserting washers between the main and lap plates. The hole diameter was 1/16-in. larger than the bolt size. The three control specimens for the series did not have washers between the plates. Thus the physical conditions affecting the slip behavior were the same for these control specimens as they were for the three control joints (OH1 series) of the oversize hole joint series. Therefore a direct comparison of the slip coefficients can be made.

The second group of three joints, designated OH2, had a hole diameter of 1-1/4-in. providing four times the maximum allowable hole clearance. These joints were also bolted up without washers.

The third group, designated OH3, also had a hole diameter of 1-1/4-in. These were bolted up with washers under the nuts in order to determine whether or not washers should be required for holes of this amount of oversize.

The fourth group of joints, designated OH4, originally had hole diameters of 1-3/16-in. which provided three times the maximum allowable hole clearance. The holes in these three joints were to be enlarged to 1-5/16-in. if the joints with the 1-1/4-in. holes indicated no significant change in slip behavior from the control specimens.

The nine joints with slotted holes had the slots placed in the middle, or main plates. This is because slotted holes located in the outside plies would normally be covered with large washers which would cause these plies to act as enclosed plates. The slots were 2-9/16-in. long and 1-1/16-in. wide. The holes in the outside plates provided the maximum allowable hole clearance of 1-1/16-in. The joints were assembled without washers.

Three joints contained slots placed parallel to the line of load. These were designed as friction-type joints and were designated SH1 (See Fig. 3). The A_n/A_s ratio was the same as that of the oversize hole joints so that the effect of slotted holes placed in the direction of slip on the slip resistance could be observed.

Six joints were designed as bearing-type joints and contained slots placed perpendicular to the line of load (Fig. 4). Three of these joints, designated SH2, were proportioned with currently used allowable stresses and failure was expected to occur by a tearing of the plate at the net section. Their net section area was equal to the bolt shear area. The net section efficiency was 60%.

The remaining three joints, designated SH3, had an increased net section area so that failure would occur by a shearing of the bolts. Earlier experimental and theoretical studies had shown that this would occur if its net section area was 36% greater than the bolt shear area.

3.2 Plate Properties

The A36 steel plate that was used for the specimens was purposely ordered to minimum strength. The plates were furnished from the same heat and were rolled 28-1/2 inches wide and 34 feet long. A 2-foot long section was cut from the middle of each plate. Standard tensile coupons were cut from this piece to evaluate the material properties. These coupons were tested in a mechanical universal testing machine equipped with an automatic load-strain recorder. The testing speed was 0.025 inches per minute until strain hardening began. The static yield load was obtained by stopping the machine 3 times during yield and allowing the machine to equalize each time. When the coupon went into strain hardening, the testing speed was increased to 0.3 inches per minute until the coupon failed. The load-strain curve for an 8 inch gage length was plotted by the automatic recorder for each coupon.

The yield point of the plates was less than the specified minimum because the testing speed was lower than the mill rate. The joints were fabricated from plates having material properties that were similar.

The results of the tensile coupon calibrations are summarized in Table 1.

3.3 Calibration of Bolts

One inch diameter A325 bolts were used to bolt up all 21 joints.

Because some joints were bolted up with washers and some without washers, two different bolt lengths were required. The bolts used in joints without washers were 5-1/4-in. long and were designated lot XB. The bolts used in joints with washers were 5-3/4-in. long and were designated lot XC. Both lots had the standard length of threads.

Representative samples of bolts from each lot were calibrated in both direct tension and torqued tension to determine their properties. Three bolts from each lot were chosen at random for each calibration. An extensometer, consisting of a counterweighted C-frame and a dial reading to the nearest ten-thousandth of an inch, was used to take elongation measurements of each bolt as it was loaded. From this information, mean load-elongation curves were obtained for each lot of bolts and are summarized in Fig. 5.

All of the bolts calibrated satisfied the minimum proof load and ultimate load requirements specified by the ASTM. Since the bolts were held at the same grip when tested as existed in the joint, the load-elongation curves used in the torqued tension calibration tests were used to determine the tension in the bolts that were installed in the joints.

It was found from the direct tension calibration tests that both lots of bolts had tensile strengths that exceeded minimum strength by 13% to 15%. In both the direct tension and torqued tension calibrations, the bolts remained elastic well above the required minimum tension.

3.4 Fabrication and Assembly of Joints

The test joints were fabricated by a local steel fabricator. In most cases, the four pieces of plate used for each joint was taken from the same plate; otherwise they were matched as closely as possible using the data obtained from the plate coupon calibration tests. The individual plates were flame cut to rough size and then milled to the specified joint dimensions. The faying surfaces were cleaned of loose mill scale and burrs. The four corner holes of each oversize hole joint assembly were then sub-drilled and reamed for alignment. The four remaining holes were then drilled through all four plies of steel to the specified size while the plates were held in alignment by steel pins in the corner holes.

The slotted holes were formed by drilling two adjacent holes in the plate and removing the metal between them.

Filler plates were welded to the lap plates on one end of each joint and the main plates were welded together at the grip end to ensure a uniformity of wedge grip action during testing.

Cleaning, assembly and instrumentation of the joints were performed at Fritz Engineering Laboratory. Before assembly the joints were cleaned with shop solvent to remove any grease or other foreign material. They were then assembled and aligned. The bolts were either installed with or without washers depending on the individual test. The turn-of-nut installation procedure was used. The bolt tensions were determined by measuring the changes in bolt length with the extensometer and then determining the corresponding bolt tension from the torqued tension calibration curve.

In all of the joints except for the three joints with hole diameters of 1-5/16-in. the bolt tension varied from the required minimum tension to 50% in excess of the required minimum tension.

When two of the joints with the 1-5/16-in. holes (OH4 series) were bolted up with washers under the nuts using the standard turn-of-nut method, half of the bolts failed to achieve proof load. The bolts were removed and the two joints were rebolted with washers placed under both the heads and the nuts. The third joint of the series was also bolted up with washers under both the head and the nut.

3.5 Instrumentation of Joints and Bolts

All of the specimens were instrumented to record their performance during testing. The friction-type joints were instrumented to record joint slip, elongation, and alignment.

Dials reading to 0.0001-in were attached to tabs tack welded to both sides of the main plate in line with the bottom row of bolts. The pointers of these gages rested on a frame that was tack welded to the lap plates in line with the tabs. Thus slip movement between the main and lap plates was measured on one line and effects due to axial strains were minimized.

Joint elongation was measured between points one gage length above the top line of bolts and points one gage length below the bottom line of bolts. These points were located on the center line of the joints, the top points being located on both faces of the main plate and the bottom points being located on both lap plates. One-half inch studs were tack welded to the plates at these points. Elongations were read from 0.0001-in. dials that read the relative movement of the studs by means of a sliding rod arrangement. The arrangement of the joint slip and joint elongation dials on one of the friction-type joints is shown in Fig. 6.

The bearing-type joints were instrumented to record joint slip, joint elongation, and also overall member elongation. The instrumentation used to record joint slip and elongation was the same as for the friction-type joints. The overall member elongation was measured between points placed as far apart on the faces of the joint as the testing machine gripping clearance would allow. The elongations were read from 0.0001-in. dials that were mounted on the top studs and connected to the bottom studs by piano wire.

Electrical resistance strain gages were attached to the sides of the main and lap plates of all of the joints to detect any eccentricity of loading caused by uneven gripping or curvature of the joint and also to determine the onset of yielding.

A number of the bolts were instrumented with electrical resistance foil strain gages cemented to their shanks. Flat areas 1-1/16-in.

long and 1/16-in. deep were milled into the shank under the bolt head to provide a mounting surface for the gages. The gages were placed on opposite sides of the shank parallel to the axis of the bolt. The gage wires passed through two holes drilled through the bolt head. This arrangement is shown in Figs. 7A and 7B.

It was discovered during the direct tension calibrations that the shanks of the bolts remained elastic into the range of bolt tension achieved by the turn-of-nut method of installation, and a linear load-strain relationship existed as shown in Fig. 8.

Since the gaged portion remained elastic it would not be as affected by the high load and very little creep would occur. On the other hand, inelastic deformation was occurring in the threads so that the overall bolt elongation could not be expected to yield consistent results.

Each gaged bolt was calibrated in direct tension in order to relate the strain readings with the tension in the bolt. During the calibration, the bolts were loaded in 10 kip increments to 50 kips and then in 5 kip increments to 65 kips. The overall bolt elongations were also checked with the extensometer. It was observed that the reduced area of shank due to the milled surfaces did not cause any measurable difference in the load-elongation relationship of the bolts as compared to the bolts without gages. The load-strain reading relationship of the gaged bolts was linear for both the loading and unloading cycles.

The gaged bolts were used in six of the bolted joints. These were: OH1-1 and OH1-2 (1-1/16-in. diam.), OH2-1 (1-1/4-in. diam., no washers), OH4-1 (1-5/16-in. diam., 2 washers), SH1-1 (slots parallel to line of load) and SH3-1 (slots perpendicular to the line of load).

Four gaged bolts were installed in each of these six joints. They were arranged in a staggered pattern in the joint as shown in Fig. 9. These were tightened in the same manner as the ungaged bolts.

3.6 Testing Procedure

All of the joints were tested in a 5,000 kip universal testing machine using flat wedge grips. Each joint was held by the top grips of the machine while dials were placed on the specimen. The dials and strain gages were all read at zero load. The bottom grips were then applied, and loading started. Load was applied in 25 kip increments until major slip occurred. At each increment all dials and strain gages were read.

For the friction-type joints, the slip behavior was observed closely. Following major slip, the dials and gages were read and load was applied in 10 kip increments until another slip, smaller than the original slip and designated as a minor slip, occurred. This loading sequence as repeated for all subsequent minor slips until the joint went into bearing, at which time the test was stopped.

For the bearing joints, the test was carried to ultimate and failure. The initial slip load was observed and the joint was then loaded in 50 kip increments until the load approached the predicted ultimate strength. The testing machine was then stopped and the dial gages were removed from the joint. A protective steel cage was then placed around the joint.

The plate failure specimens were then loaded to failure, which occurred when the main plate tore apart at the top line of slots.

The bolt failure specimens were loaded until the top row of bolts failed in shear.

After the joints were removed from the testing machine, each one was dismantled. The condition of the faying surfaces was inspected. The fracture surfaces of the plate failure specimens were inspected. A sawed section of one of the bolt failure specimens was taken to inspect the condition of the bolts and of the slotted holes.

3.7 Loss-in-Tension Studies

Immediately after the nut on a high-strength bolt is tightened a loss in bolt tension occurs. This is thought to be as a result of an elastic recovery accompanied by a creep or plastic yield in the threaded portions. In addition, some plastic flow may occur in the steel plates under the head and nut. Some research has been done on holes that had the standard hole clearance of 1/16-in. Only a few relaxation tests have been conducted on larger holes.

It was desirable to evaluate the effect on relaxation of holes that were substantially oversize. The largest hole size studied was 5/16-in. oversize, or 2-1/2 times the amount of any previous studies which evaluated holes 1/8-in. oversize. The effect of the enclosed slotted holes on loss of bolt tension was also evaluated.

Since the load-elongation relationship of the bolt shanks was linear within the range of bolt tension used, the bolts with the strain gages cemented to their shanks should give an accurate indication of the bolt tension at any time. Thus a meaningful relationship of the bolt tension variation with time could be established. The six bolted joints containing the gaged bolts provided a good representative sample of all of the joints in the study.

The six joints were placed horizontally in a location where they were not disturbed for the duration of the study. (See Fig. 10). Strain gage readings were taken at the moment each bolt was installed. Subsequent readings were taken at 1 minute, 5 minutes, 1 hour, 1 day, 1 week, 2 weeks and 1 month after installation. The strain gage indicator was left connected to the strain gaged bolts through a switch box for the duration of the study. In addition to the strain gage readings, extensometer readings were taken at the same intervals on all 8 bolts of each joint. This provided an opportunity to correlate the strain readings on the bolt shanks with the bolt elongation readings.

At the completion of the study, the six joints were tested using the standard procedure. During each test, strain readings were taken so that the changes in bolt tension during testing could be observed.

In order to check the accuracy of the bolt gage readings over an extended period of time, gaged bolts of the same lot were installed in a load cell as shown in Fig. 11. The load cell was made of hardened tool steel and had a hole 1-1/16-in. in diameter through its center through which the bolt was inserted. Four strain gages were cemented to the outside of the load cell, two placed horizontal and two placed vertical. They were connected to a strain gage indicator in a wheatstone bridge arrangement.

One-half inch thick A36 steel plates were placed over each end of the load cell so that the behavior of the plates under the head and nut would be similar to the behavior of the plates in the actual joints. Three sets of these plates were used, one set for each of the three hole diameters used in the oversize hole specimens. The total grip of the assembly was 4 inches. Thus the conditions that affected the relaxation behavior of a bolt in the test joints were closely approximated.

The bolt to be studied was installed while the load cell assembly as firmly held in a vise. The bolt gages and the load cell gages were connected to separate strain gage indicators that were set to indicate a load of 60 kips. The nut was tightened by a hand wrench until the desired load was reached. Readings were taken for both the bolt tension and load cell deformation at intervals of one minute, 5 minutes, one hour, and each day for a week. Overall bolt elongation readings were also taken using the extensometer.

4. TEST RESULTS AND ANALYSIS

4.1 Effect of Hole Size on Bolt Tension and Installation

It is of interest to examine the effect of varying hole diameters on the ease of installation, degree of scouring and clamping force of bolts installed by the turn-of-nut procedure.

The bolts in the OH1 joints (1-1/16-in. hole diameter) were installed without washers. This was in accordance with the present specifications for bolted joints which permits installation without washers when using the turn-of-nut method. There was no difficulty achieving a bolt tension above the required preload in these joints. The tension achieved in the 24 bolts of the 3 control joints ranged between 116% and 149% of the required preload as shown in Fig. 12. The average bolt elongations and tensions for each joint are listed in Table 2. The mill scale on the plate area under the turned element around the 1-1/16-in. holes was slightly galled as shown in Fig. 13. A slight depression occurred under the bolt head, as shown in Fig. 14. This nominal amount of damage indicated that washers are not required under the head or the turned element for holes that contain the nominal amount of clearance.

The bolts in the 3 joints of the OH2 series (1-1/4-in. hole diameter) were installed without washers while the bolts for the OH3 series (also 1-1/4-in. hole diameter) were installed with washers under the turned elements. There was no difficulty achieving bolt tensions above the minimum required tension in all six joints. The average bolt elongations and tensions for the 2 series are summarized in Table 2. The range of bolt tensions achieved for each series is shown in Fig. 12.

As can be seen in Fig. 13, the average bolt tensions for the two groups containing 1-1/4-in. holes were about equal (118% of proof load) but were noticeably lower than the average tension in the control groups (13% of proof load). An examination of the plate areas under the bolt heads indicated depressions had occurred during tightening (Fig. 15) that were greater than the indentations that had occurred under the heads of the bolts in the control joints. This meant that the longations of the bolts in the 1-1/4-in. holes were smaller than the elongations in the control joints and hence the bolt tensions were reduced.

Observation of the plate areas under the nuts of the OH2 series joints indicated that severe galling of both the plate and the nut had occurred during installation. The damage to the plate and the nut is shown in Figs. 16 and 17. For comparison, the surface condition of the plate where washers were used under the nuts in the OH3 series is shown in Fig. 18. Only a slight depression occurred under the washer. It can be seen from Fig. 12 that the use of washers in the 1-1/4-in. holes did not affect the average clamping force of the bolts. However, the scatter in bolt tension for the bolts that were installed without washers was nearly twice as large as the scatter in the bolt tension for the bolts that were installed with washers. Hence, the clamping force for the joints with washers was more uniform.

The holes in the OH4 series joints were drilled from the original 1-3.16-in. diameter to 1-5/16-in. diameter after the results of the studies on the slip behavior of the OH2 and OH3 series were observed. The bolts in two of the three OH4 series joints were installed with washers placed under the nuts. This was done after observing the severe galling that occurred in the OH2 series where the bolts were installed without washers. When the bolts in these two specimens were tightened by the standard turn of nut procedure, half of the 16 bolts failed to achieve their required minimum tension. The bolts were then removed from the joints. Inspection of the two joints revealed that the bolt heads had recessed severely into the plate around the holes. This condition was far more severe than the recessions that occurred in the OH2 and OH3 series, as shown in Fig. 19. In this instance, the elongations of the bolts were reduced sufficiently so that the bolt preload was less than the required minimum tension.

All three OH4 joints were then rebolted with washers installed under both the heads and nuts. This time there was no difficulty achieving bolt tensions above proof load. The range of bolt tensions achieved for the OH4 series joints both with and without washers installed under the heads are compared in Fig. 20. The range of tensions achieved for bolts installed with washers under both the head and the nut was from 110% to 144% of proof load with an average tension of 125% of minimum tension. This compares with the range of bolt tensions achieved in the bolts in the control joints, as shown in Fig. 12.

The results of these studies can be extended to determine the maximum allowable hole clearance for other sizes of A325 bolts for the given grip length in A36 steel plate. The difficulty in achieving proof load tension was a result of the bolt depressing into the plate around the hole. In the holes with the 5/16-in. clearance, the bolt heads recessed severely into the plate because the bearing pressure between the flats of the heads and the plate was initially too high. This was not the case for the bolts that were installed in the holes with 1/4-in. clearance. It can be assumed that the bearing pressure that was developed under the flat areas of the bolt heads with 1/4-in. clearance holes was the maximum allowable bearing pressure. This bearing pressure was 72 ksi when the bolt preload was 20% in excess of the required tension. The maximum hole clearance for any size bolt may then be computed on the basis that the area of plate remaining under the flat of the head must be sufficient to permit a maximum bearing pressure of 72 ksi when the bolt is installed.

The results of these computations are summarized in Table 3. All of the hole diameters have been rounded off to the nearest sixteenth of an inch. The maximum allowable hole clearance for bolts equal to or less than one inch in diameter is 3/16-in. For bolts with diameters greater than one inch diameter 5/16-in. hole clearance is permissible.

4.2 Loss-in-Tension of Bolts with Time

The results of the study relating the loss-in-tension of high-strength bolts with time following installation are listed in Table 4. The time-tension relationship of bolt XB29 that was installed in joint OH1-2 is shown in Fig. 21. This was typical of the behavior of all 24 gaged bolts installed in the 6 joints included in the study.

The loss-in-tension one minute after installation agreed with the one minute losses reported in a previous investigation,[7] where the loss-in-tension for heavy-headed bolts and nuts ranged between 2% and 4% of the initial clamping force.

Nearly all of the loss for each bolt occurred within the first few hours after installation. Also, none of the variations of hole diameter or the presence of slots had any significant effect on the percent loss-in-tension of the bolts during the study period of one month. The extensometer readings indicated that the ungaged bolts behaved the same as the gaged bolts.

The load cell studies are compared with the bolt gage readings in Table 5. Since virtually all of the losses in the bolts installed in the joints occurred within a week after installation, the load cell studies were also conducted for one week. The results showed good agreement between the bolt strain measurements and the load cell. The maximum error was 2-1/2% of the initial clamping force.

4.3 Slip Behavior

The slip resistance of a bolted joint is a function of its slip coefficient and the bolt preload. The slip coefficient has been defined as:[3] $K_s = P_s/NT_i$, where K_s is the slip coefficient, P_s the slip load, N the number of slip planes and T_i the total initial clamping force.

The total clamping force was taken as the sum of all of the bolt tensions measured approximately one minute after installation. The slip coefficients for each of the joints are summarized in Table 2. The load-slip and load-joint elongation relationships for typical joints of each series are shown graphically in Figs. 22 to 28.

The load-slip response of the joints was linear until the load approached the region of major slip. The dial gages that recorded slip moved very slowly in this region. Occasionally, there would be a slight noise and the slip dials would indicate a sudden movement of about 0.0001-in. This was probably caused by the extension of the slip zone into the joint. When the load approached the major slip load the dials usually began to move faster and when major slip occurred, there was a loud noise accompanied by a sudden movement (about 0.04-in.) of both the slip and elongation dials which caused a drop in the testing machine load. This initial slip was never equal to the hole clearance of the joint. Subsequent loading of the bolted joint produced small additional slips until the joint was in bearing. These small slips seldom occurred at higher loads than the major slip load. The number of smaller slips increased as the hole diameter increased. The reason that the initial slip did not bring the joint into bearing was due to the decrease in load caused by the slip. In an actual structure the load may remain constant and the joint would slip into bearing at the initial slip. An examination of Figs. 22 to 28 shows that each joint of the OH series behaved in a similar fashion.

The three joints of the OH1 series which had the nominal hole clearance of 1/16-in. served as control specimens. The average slip coefficient for these three joints was 0.29. This value is comparable to the average slip coefficient of 0.34 obtained by Nester[16] from a series of bolted connections that were made from the same heat of steel. Tests conducted at the University of Washington[17] on A36 steel bolted joints yielded comparable results.

Investigation of the faying surfaces of the OH1 joints (See Fig. 39) indicated that damage to the mill scale surface was mostly confined to the areas immediately adjacent to the holes. This is in accordance with the theory that the areas immediately adjacent to the holes of a bolted joint are the areas of highest contact pressure and therefore provide most of the slip resistance.

The OH2 and OH3 joints with the 1/4-in. hole clearance provided slip resistance comparable to the OH1 tests. The average slip coefficient for both the OH2 and OH3 series was 0.28. Inspection of the faying surfaces indicated that most of the surface damage occurred around the holes (See Fig. 30). This also showed that the pressure distribution in these joints was similar to the pressure distribution that existed in the control joints. The damage was more severe for the 1/4-in. hole clearance joints because the distance of slip was four times as great.

The three joints of the OH4 series which had hole clearances of 5/16-in. showed a decrease in slip resistance. The average slip coefficient for these joints was 0.24. Inspection of the faying surfaces after testing (See Fig. 31) also showed that most of the surface damage occurred around the holes. The damage for these joints was the most severe of the oversize hole joints because the greatest amount of slip occurred.

The three friction joints of the SH1 group had slotted holes in the enclosed plates that were placed parallel to the line of load. These joints also showed a decrease in the slip coefficient. The average slip coefficient for the series was 0.20. Inspection of the faying surfaces (Fig. 32) shows severe mill scale disturbance over the entire face of the joint. This resulted from the large amount of slip (1-9/16-in.) permitted by the slotted holes.

The slip behavior of three of the bearing joints (SH2-1, SH2-2, and SH3-1) was different from the behavior of the rest of the joints.

The behavior of these three joints prior to major slip was basically the same as the other joints; slow dial movements with an occasional sudden movement of 0.0001 inch. When major slip occurred there was no loud noise or drop of load. Instead, the dials began to move very rapidly while the load continued to increase. The total amount of rapid dial movement was enough (0.30-0.05 in.) to be considered as a major slip. Following this the joints underwent a few minor slips until the bolts went into bearing. The slip coefficients of the six bearing joints of groups SH2 and SH3 are summarized in Table 2. The average slip coefficients for the SH2 and SH3 series were 0.23 and 0.21 respectively.

The average slip coefficients of all of the joint series are compared in Fig. 33. It is observed that the average slip coefficient for the OH2 and OH3 series was about the same as the average slip coefficient of the OH1 joints. There was a decrease in the slip coefficient for the OH4 joints. This indicates that for 1-in. bolts there is no decrease in the slip coefficient for holes with up to 1/4-in. clearance. The slip coefficients for all of the slotted holes were also lower than the average slip coefficient of the control joints.

A possible hypothesis to explain the reduced slip resistance of the OH4 joints (5/16-in. clearance) and the slotted hole joints is based on the theory that the greatest contact pressure between two plates bolted together occurs immediately adjacent to the hole. High frictional forces that are proportional to the contact pressure and the interlocking of the surface irregularities in these areas constitute a major portion of the resistance of the bolted joint to slip. Removal of a large portion of this area, as in the case of the OH4 joints with 5/16-in. hole clearance and the slotted holes, causes very high contact pressures immediately adjacent to the hole which tends to flatten the surface irregularities. This reduces the slip resistance of the joint. This reduced resistance to slip should be taken into consideration in the design of friction-type joints containing large oversize or slotted holes.

4.4 Changes in Bolt Tension During Testing

The results of the study to determine the changes in bolt tension during testing of the six joints with gaged bolts are summarized in Table 6. The results listed are the averages of the four gaged bolts of each joint. The behavior of a typical bolt in joint OH2-1 up to slip is shown in Fig. 34. The behavior of the four gaged bolts in joint SH2-3 up to joint failure is summarized in Fig. 35.

The percent change in bolt tension at time of slip for joint OH1-2 was observed to be much larger than for joint OH1-1. This was because joint OH1-2 yielded at the net section before major slip occurred.

The changes in bolt tension were analogous to the changes observed in earlier studies.[15,16] The presence of oversize or slotted holes did not greatly affect the changes in bolt tension during loading.

4.5 Effect of Transverse Slotted Holes on the Ultimate Strength of The Joint

The three joints of the SH2 series were designed to fail by tearing of the plates. The results of these tests are summarized in Table 7. The load-joint elongation and load-specimen elongation relationship of joint SH2-3 is summarized in Fig. 36.

In all cases the interior slotted plate failed at the first row of slots. Fig. 37 shows the deformation that occurred in the slotted holes of joint SH2-2 at failure.

The ultimate load for all 3 specimens was roughly 110% of the predicted loads based on the coupon tests. This behavior is in agreement with the results of earlier studies conducted on bolted joints with standard round holes.

The three joints of the SH3 series were proportioned so that failure would occur by shear of the bolts. The geometry of the joints was based on the assumption that minimum strength bolts were to be used for the tests. Joint SH3-1 was bolted up with bolts of the high strength XC lot. The shear strength of the bolts exceeded the plate capacity and the joint failed by a tearing of the plate.

A new lot of bolts specified to be of minimum strength was ordered. This lot, designated XE, was tested in shear jigs with both slotted and round holes. The average ultimate shear strength of the bolts in the slotted hole shear jigs was 84.3 ksi while the ultimate shear strength in the round hole was 81.3 ksi. This was caused by a ballooning of the plate as the bolt bearing caused deformation on the flat portion of the slot as shown in Fig. 38. This caused a shifting of the shear plane with a resultant increase in the shear area of the bolt shank.

Bolts from the XE lot were then installed in joints SH3-2 and SH3-3. The results of these tests are also summarized in Table 7. The deformation of a bolt and the plates of joint SH3-2 are shown in Fig. 39. In both cases failure occurred when the head end of one of the two top bolts sheared off.

The average bolt shear stress at ultimate was about 6% lower in both joints than was predicted from the slotted hole shear jig tests. The sawed section of joint SH3-2 (See Fig. 40) shows the deformation of the bolts and of the enclosed plate.

It can thus be concluded that the presence of slotted holes in the enclosed plates of a bolted joint does not reduce the ultimate strength of either the plates or the bolts in shear.

5. SUMMARY

On the basis of this study the following conclusions have been reached:

1. 1-in. A325 bolts installed by the turn-of-nut method in holes with a 1/4-in. clearance achieved average preloads 20% above the required bolt tension. Washers under the turned element are recommended to prevent severe galling. Bolts installed in holes with a 5/16-in. clearance required washers under both the head and the turned element to achieve preloads in excess of the required bolt tension.

2. Oversize or slotted holes do not greatly affect the losses in bolt tension with time following installation. Virtually all of the losses occurred within one week after installation. The loss in tension was about 8% of the initial preload.

3. The slip behavior of joints with oversize or slotted holes was similar to the slip behavior of joints with holes of nominal size. There was a series of small slips before the joint went into bearing. The number of small slips increased as the distance of slip increased.

4. The average slip coefficient for the joints with 1/4-in. hole clearance was about the same as the slip coefficient for the con-

trol joints. The joints with 5/16-in. clearance holes showed a 17% decrease in the slip coefficient. The slip coefficient for slotted hole joints showed a 22% to 33% decrease when compared to normal test specimens.

5. Changes in bolt tension during testing were not greatly affected by the presence of oversize holes or of slots in the enclosed plates. All changes in bolt tension at major slip were within the previously observed range for change in tension at slip.

6. Slotted holes placed perpendicular to the line of load in the enclosed plates of a bolted joint did not reduce the tensile strength of the plates or the shear strength of the bolts.

6. TABLES AND FIGURES

TABLE 1

Material Properties Determined by Coupon Tests

Coupon No.	Static Yield Stress (psi)	Yield Stress (a) (psi)	Ultimate Tensile Stress (b) (psi)	% Elong. in 8 in. (%)	% Red. in Area (%)
P1-1	29,600	31,600	61,000	34.0	64.1
P1-2	29,000	31,200	61,600	33.2	62.0
P1-3	29,000	32,400	61,000	33.5	62.6
P2-1	29,300	32,600	60,500	36.2	64.1
P2-2	28,500	31,800	59,300	35.0	63.1
P2-3	29,200	32,200	60,200	33.8	61.0
P6-1	30,100	31,200	61,800	29.0	61.6
P6-2	28,200	31,200	60,700	34.0	63.6
P6-3	29,600	31,600	61,700	33.8	65.0
P7-1	29,800	31,600	61,100	34.4	64.8
P7-2	28,800	30,600	60,100	32.5	64.9
P7-3	29,900	31,400	61,800	32.5	64.5
P8-1	29,900	32,500	61,100	31.9	62.5
P8-2	29,800	31,800	62,800	31.2	61.7
P8-3	29,300	30,900	61,100	----	----
Avg.	29,300	31,600	61,000	33.2	63.3
Std. Dev.	560	530	730	1.7	1.4

(a) Mill Report: $\sigma_y = 38,800$ psi.

(b) Mill Report: $\sigma_{ult} = 62,300$ psi.

TABLE 2

Test Results - Slip Behavior of All Joints

Joint	Hole Diam.	Average Bolt Elongation	Initial Bolt Tension	Initial Slip Load	Slip Coefficient
OH1-1	1-1/16"	.0213	551.6	314.5	0.285
OH1-2	1-1/16"	.0227	558.0	327.5	0.293
OH1-3	1-1/16"	.0227	570.4	322.5	0.283
Average					0.287
OH2-1	1-1/4"	.0178	522.8	274.5	0.263
OH2-2	1-1/4"	.0119	422.0	242.5	0.290
OH2-3	1-1/4"	.0132	474.5	295.0	0.312
Average					0.282
OH3-1	1-1/4"	.0143	495.2	286.5	0.290
OH3-2	1-1/4"	.0139	482.5	267.0	0.277
OH3-3	1-1/4"	.0135	473.5	260.0	0.274
Average					0.280
OH4-1	1-5/16"	.0151	502.6	265.0	0.264
OH4-2	1-5/16"	.0173	531.2	253.5	0.238
OH4-3	1-5/16"	.0174	533.1	236.0	0.222
Average					0.245
SH1-1	Slotted	.0154	504.0	185.5	0.184
SH1-2	(Parallel	.0162	524.1	199.0	0.190
SH1-3	to line	.0191	549.5	237.0	0.215
	of load)				
Average					0.196
SH2-1	Slotted	.0223	573.9	248	0.237
SH2-2	(Perpen-	.0230	574.5	220	0.192
SH2-3	dicular	.0161	525.7	262.5	0.250
	to line				
	of load)				
Average					0.226
SH3-1	Slotted	.0223	568.5	225	0.200
SH3-2	(Perpen-	.0232	475.4	210	0.221
SH3-3	dicular	.0250	480.2	214	0.223
	to line				
Average	of load)				0.215

TABLE 3

Allowable Hole Clearance for Different Hole Sizes

Bolt Size	Proof Load	Min. Area	Flat Area*	Max. Hole Area = Flat Area-Min. Area	Max. Hole Diam.	Amount Clearance	Bearing Pressure
1/2	12	.200	.601	0.401	11/16"	3/16"	62.6
5/8	19	.315	.887	0.570	13/16"	3/16"	62.0
3/4	28	.465	1.227	0.761	15/16"	3/16"	62.5
7/8	39	.647	1.623	0.973	1-1/16"	3/16"	62.9
1	51	.846	2.074	1.224	1-1/4"	1/4"	72.0
1-1/8	56	.930	2.580	1.646	1-7/16"	5/16"	70.3
1-1/4	71	1.180	3.142	1.962	1-9/16"	5/16"	69.5
1-3/8	85	1.410	3.758	2.340	1-11/16"	5/16"	67.0
1-1/2	103	1.710	4.430	2.713	1-13/16"	5/16"	66.9

* The area of a circle with a diameter equal to the width across the flats.

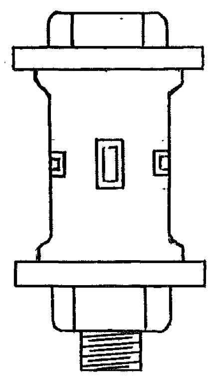
TABLE 4

Loss-in-Tension of Bolts Installed in Joints

Joint	Average Loss in Bolt Tension %					
	1 Min.	5 Mins.	1 Hr.	1 Day	1 Week	4 Weeks
OH1-1	1.21%	1.69%	3.10%	4.12%	4.28%	5.52%
OH1-2	1.33%	1.72%	2.16%	2.66%	3.08%	5.30%
OH2-1	1.65%	2.43%	3.00%	4.22%	4.68%	6.18%
OH4-1	3.18%	3.34%	3.34%	3.34%	3.34%	3.34%
SH1-2	4.48%	4.90%	5.07%	5.45%	5.58%	6.94%
SH2-3	3.34%	4.03%	4.52%	4.52%	4.52%	5.72%

TABLE 5

Results of the Load Cell Studies on Single Bolts



Hole Clearance in.	Initial Bolt Tension, Kips	Loss in Tension, Kips									
		1 Min.		5 Min.		1 Hr.		1 Day		1 Week	
		Bolt	Cell	Bolt	Cell	Bolt	Cell	Bolt	Cell	Bolt	Cell
1/16 in. (Std)	60.0	1.0	0.6	1.3	1.4	1.3	1.9	1.3	2.5	1.3	2.6
1/4 in.	59.5	0.8	0.4	1.3	0.9	1.6	1.3	2.0	1.4	2.3	1.4
5/16 in.	60.7	0.7	0.2	1.1	0.4	1.5	0.6	1.5	0.8	1.5	0.9

TABLE 6

Joint	Slip Load	% Change in Tension		
		200^k	Slip	After Slip
OH1-1	314.5	4.3%	12.1%	16.4%
OH1-2	327.5	6.1%	23.0%	0
OH2-1	274.5	4.3%	10.3%	7.6%
OH4-1	265.0	6.7%	12.4%	21.2%
SH1-2	185.5	-	9.0%	9.0%
SH2-3	262.5	1.9%	2.9%	-

TABLE 7

Test Results - Bearing Joints

1. Plate Failure Tests

Joint	Net Plate Area in^2	Ultimate Load Kips	Ultimate Tensile Stress Ksi	Coupon Ultimate Tensile Stress
SH2-1	12.46	820	65.9	61.6
SH2-2	12.42	854	68.6	62.5
SH2-3	12.42	852	68.5	62.0
SH3-1	17.37	1104	63.6	61.6

2. Bolt Failure Tests

Joint	Net Bolt Shear Area in^2	Ultimate Load Kips	Apparent Avg. Ultimate Shear Stress Ksi	Shear Jig Ultimate Shear Stress Ksi
SH3-2	12.56	1000	79.6	83.8
SH3-3	12.56	1006	80.0	83.8

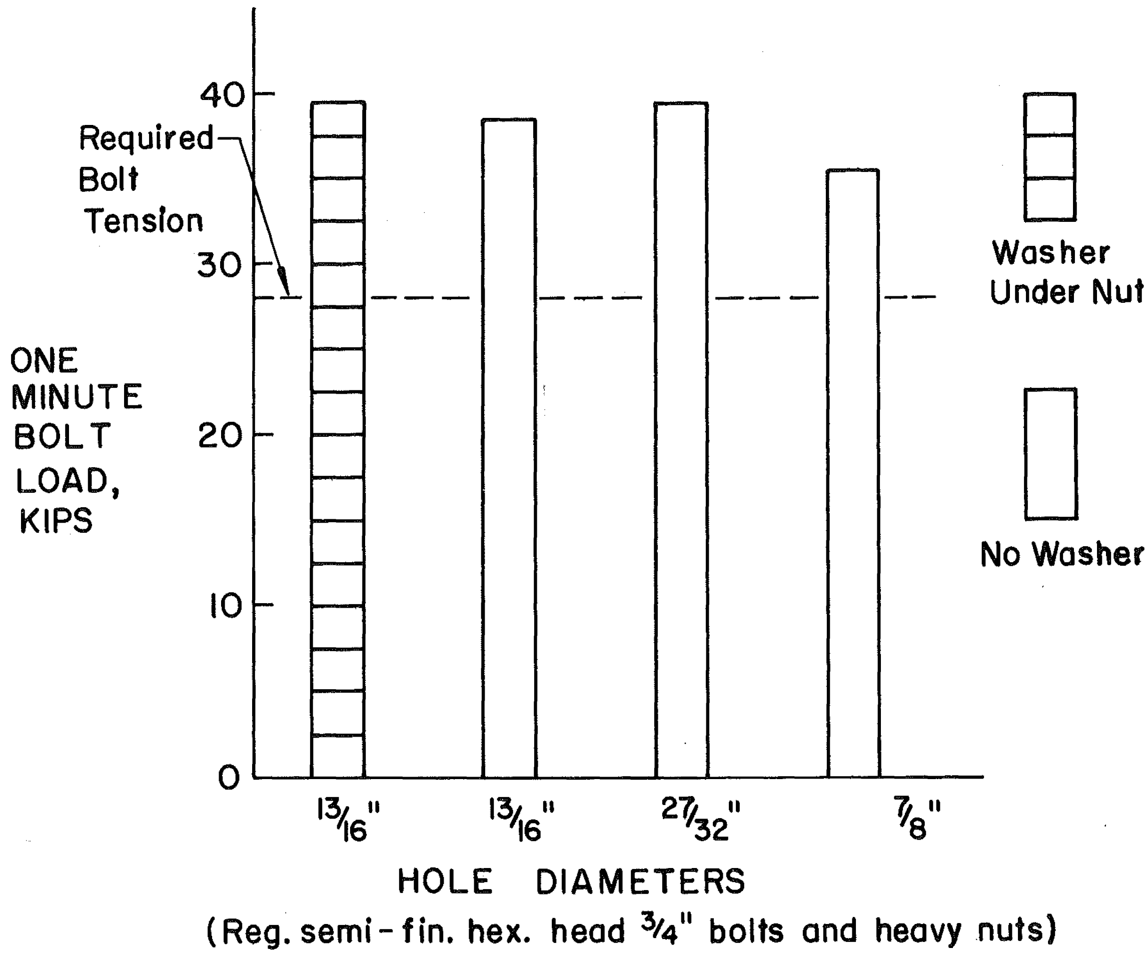
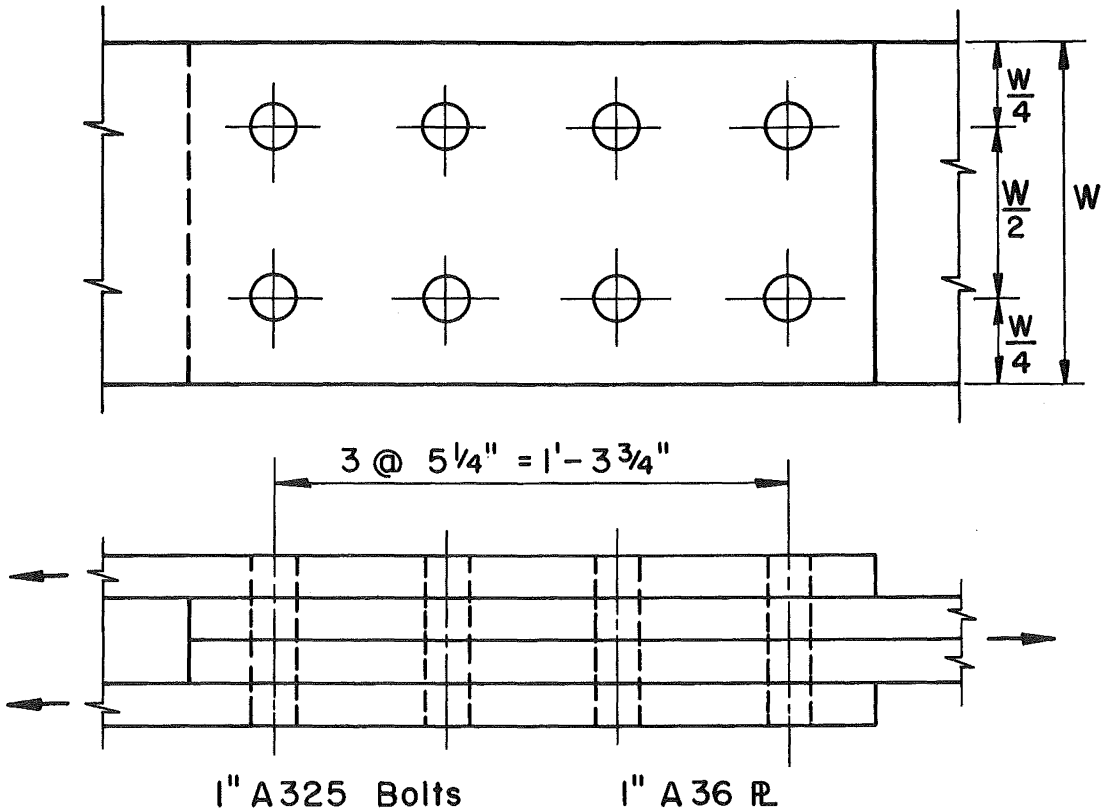


FIG. 1. Effect of Hole Size on Bolt Tension Induced by Turn-of-Nut



SERIES	NO. TESTED	HOLE DIA.	WIDTH "W"
OH1	3	1 1/16"	6.40"
OH2	3	1 1/4"	6.78"
OH3	3	1 1/4"	6.78"
OH4	3	1 5/16"	6.65"

FIG. 2. Oversize Hole Test Specimens

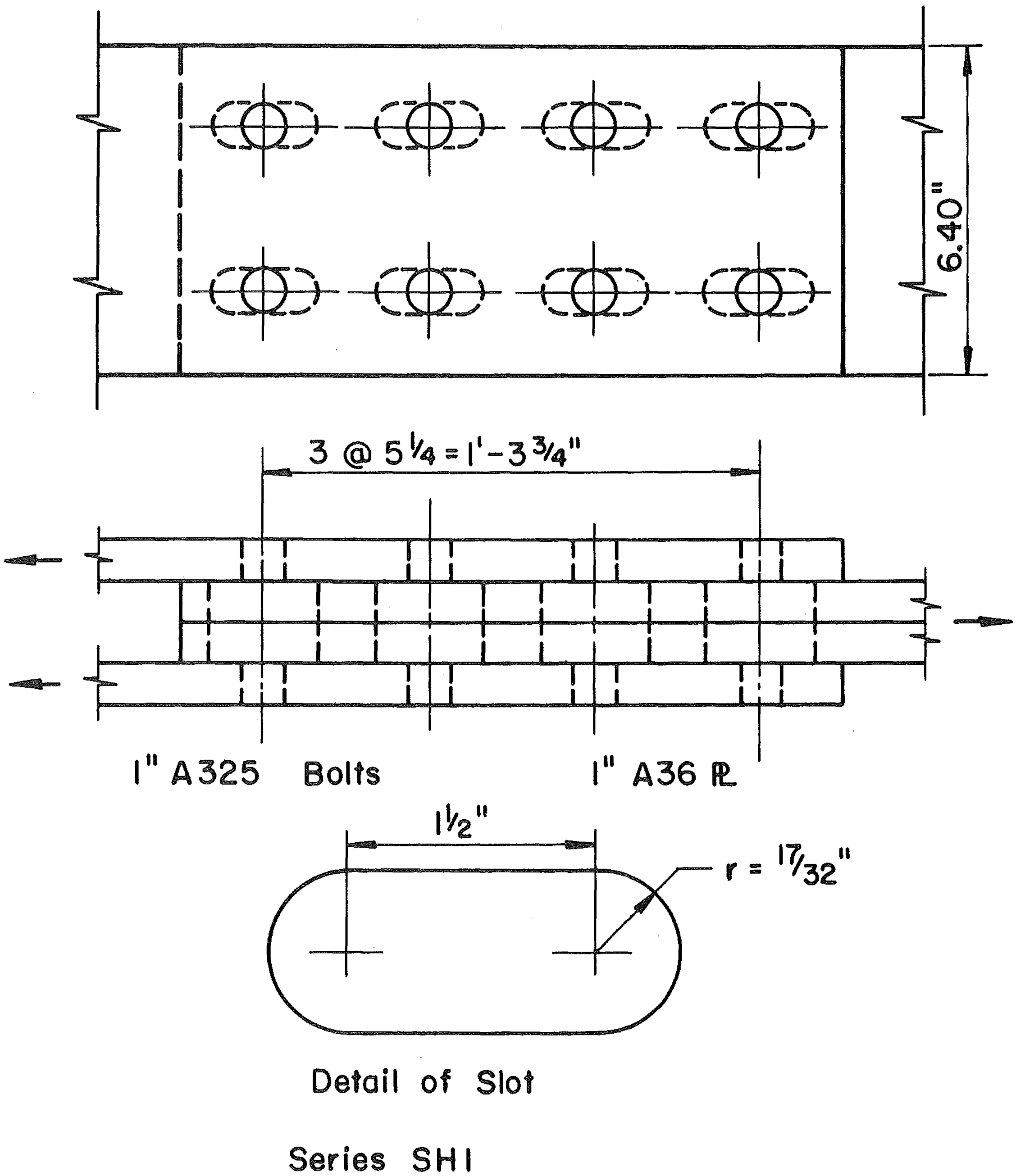
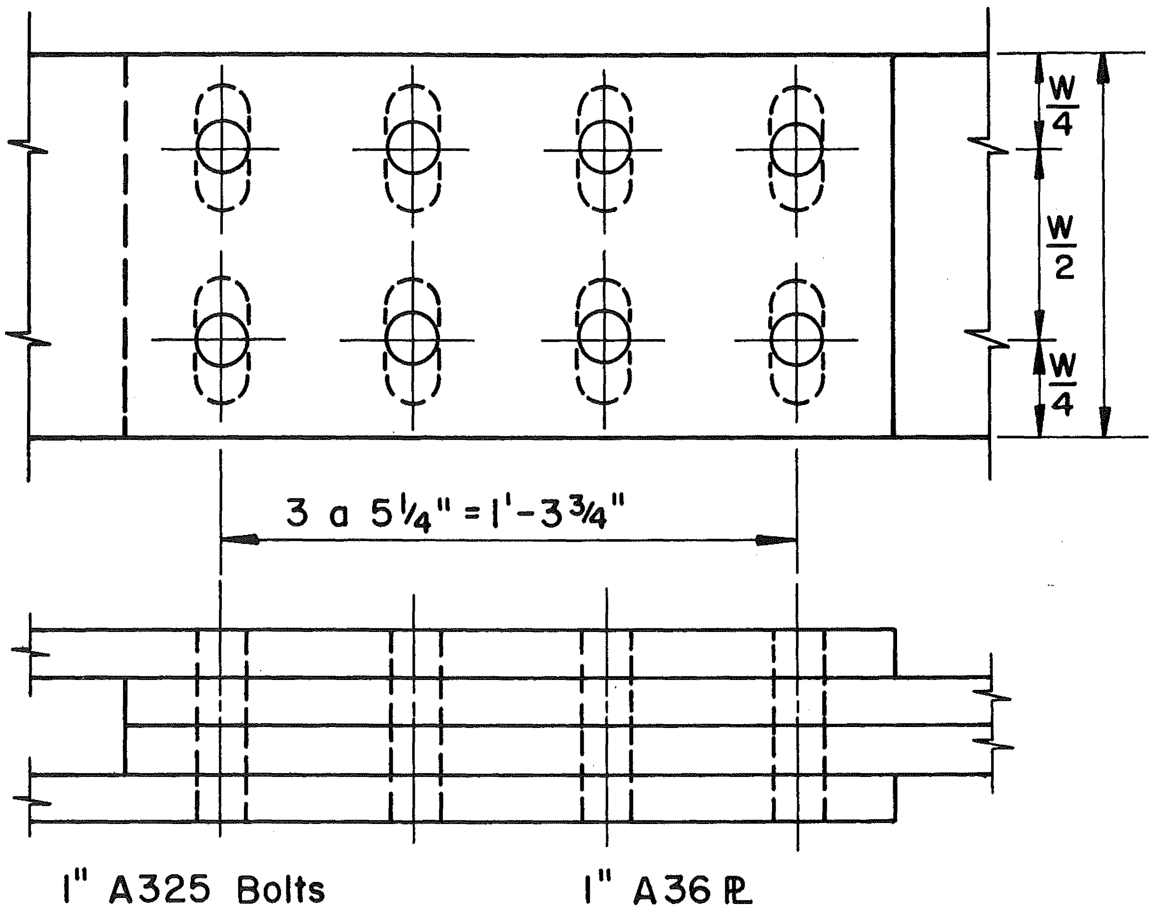


FIG. 3. Test Specimens - Slotted Holes Parallel to the Line of Load



SERIES	NO. TESTED	WIDTH "W"	A_n/A_s
SH2	3	11.42"	1.00
SH3	3	13.68"	1.36

FIG. 4. Test Specimens - Slotted Holes Perpendicular to the Line of Load

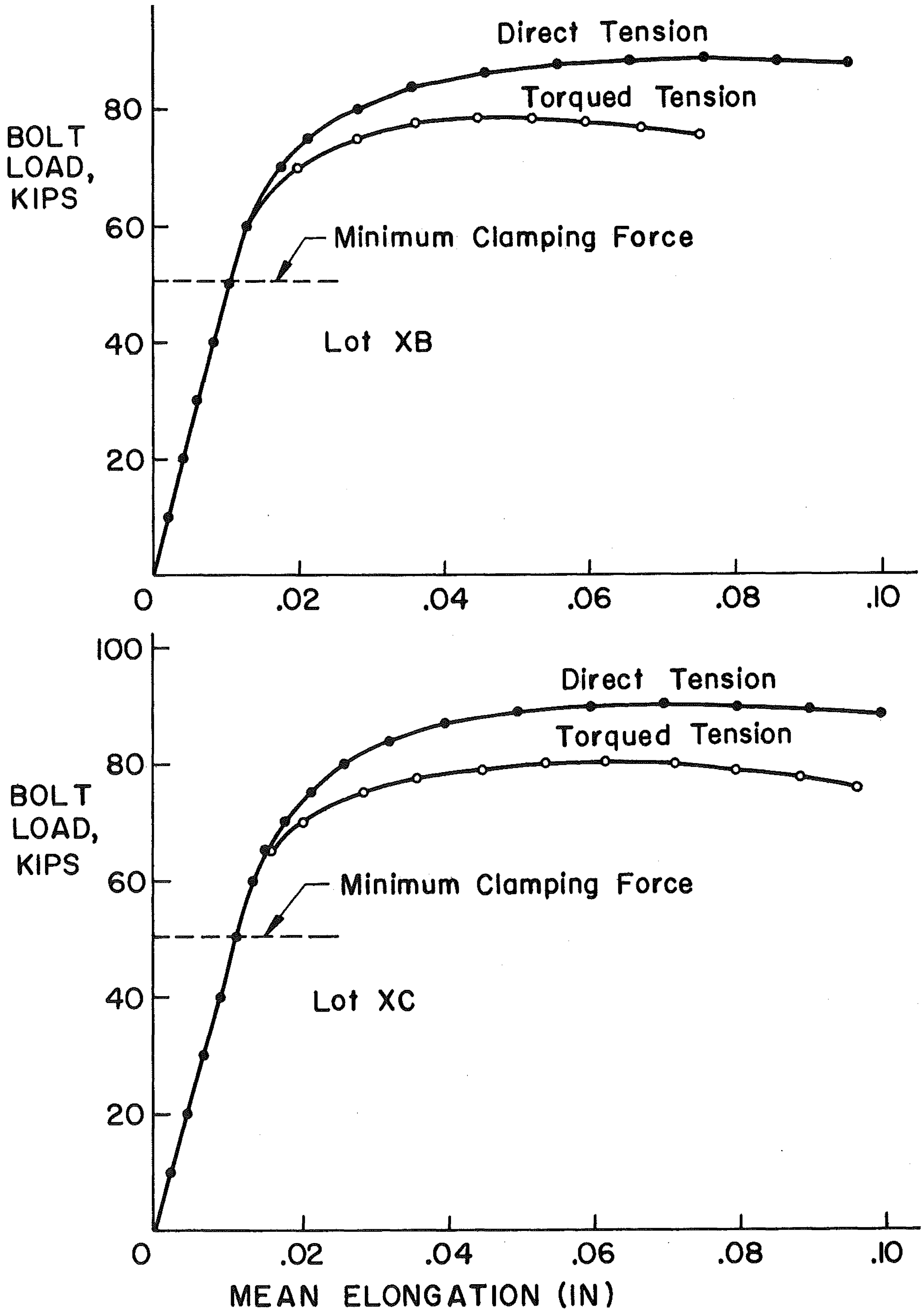


FIG. 5. Bolt Calibrations

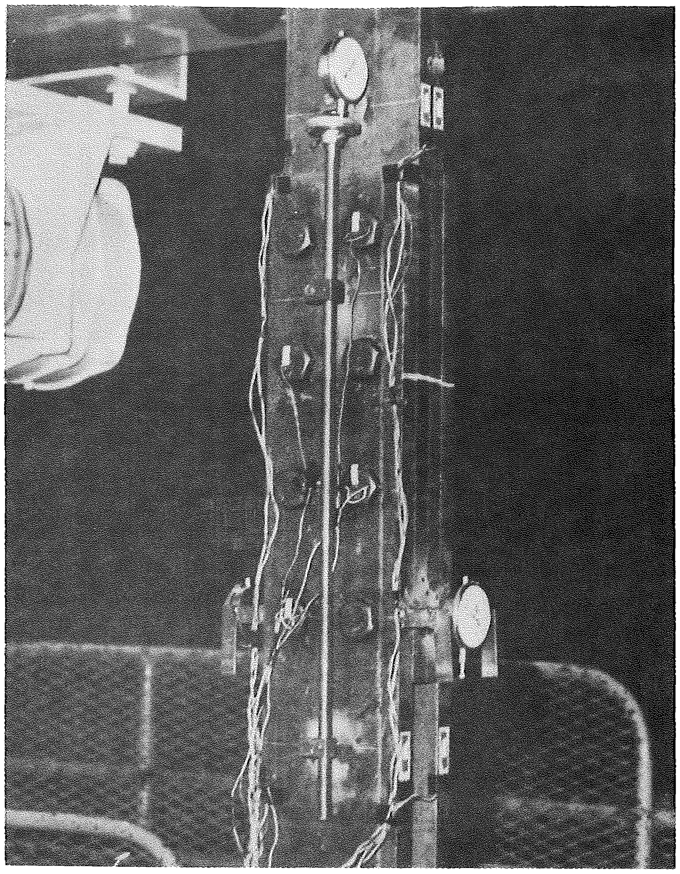


FIG. 6. Friction-Type Joint Showing Arrangement of Dials and Gages

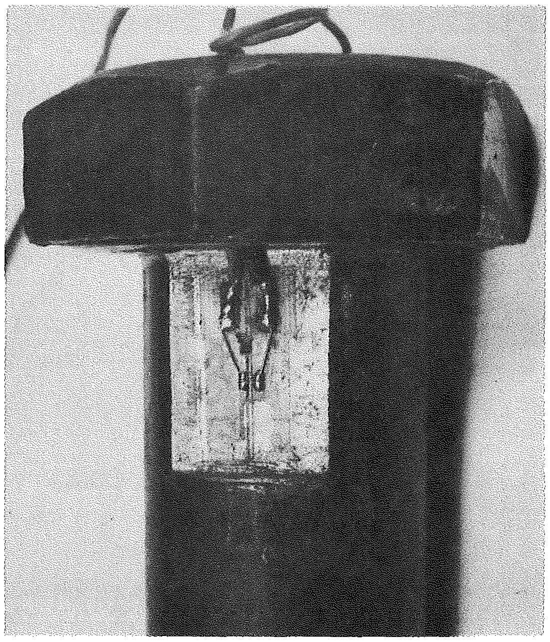


FIG. 7A. Mounting of Strain Gages on Milled Area of Bolt Shank

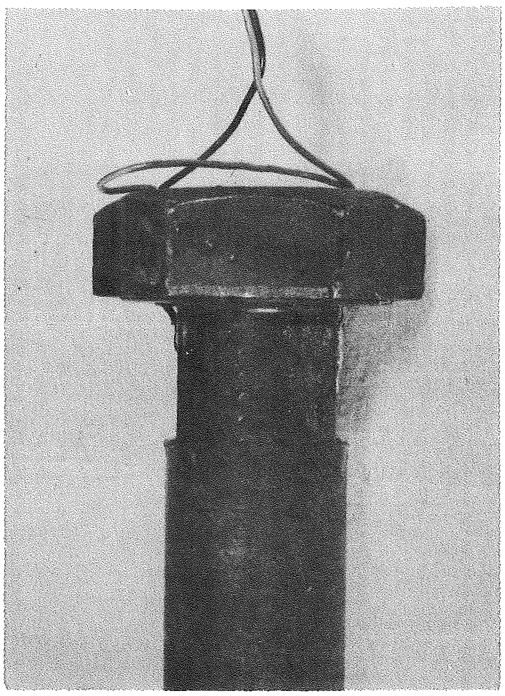


FIG. 7B. Strain Gages Mounted on Opposite Sides of Bolt Shank

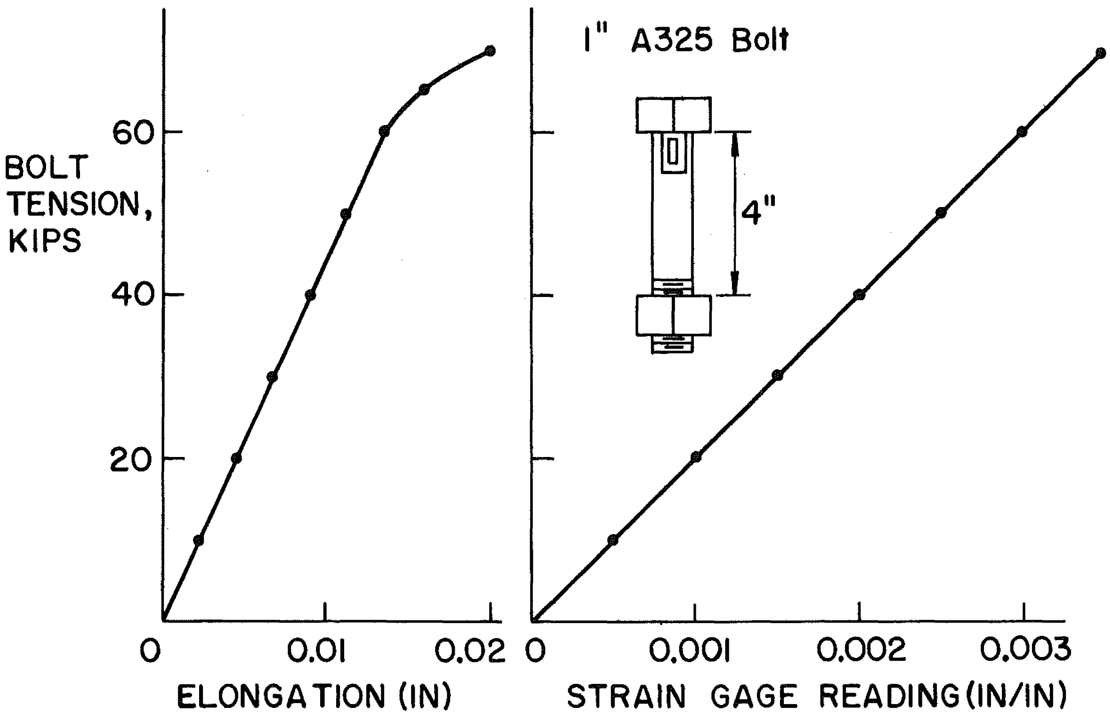


FIG. 8. Calibration of Gaged Bolts

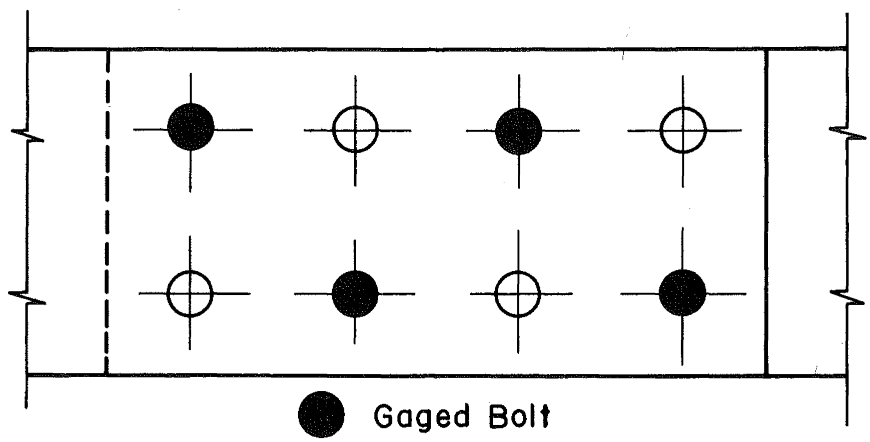


FIG. 9. Location of Gaged Bolts in Joint

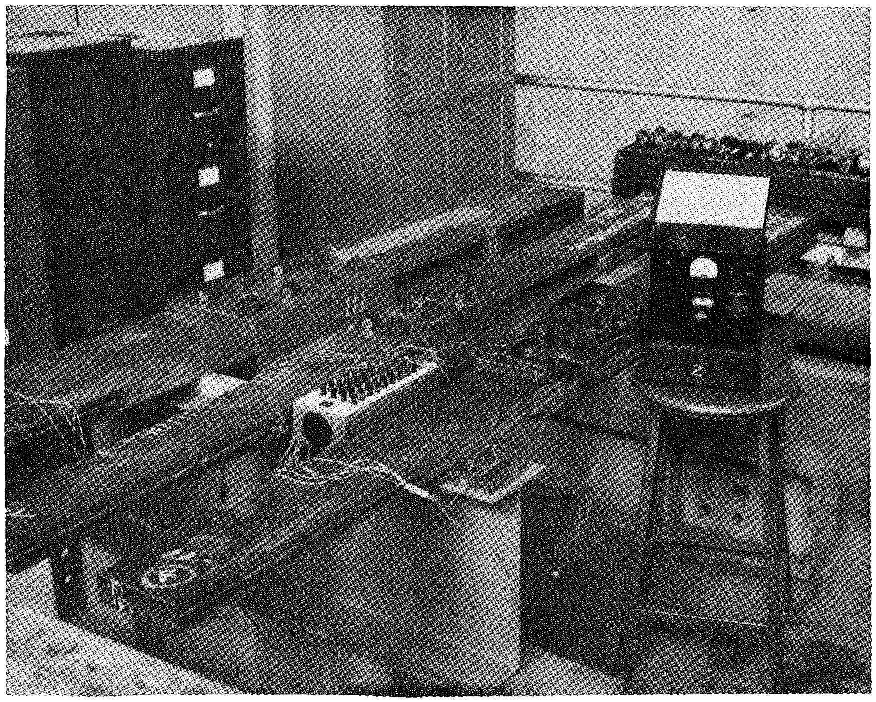


FIG. 10. Arrangement for Joint Loss-in-Tension Study

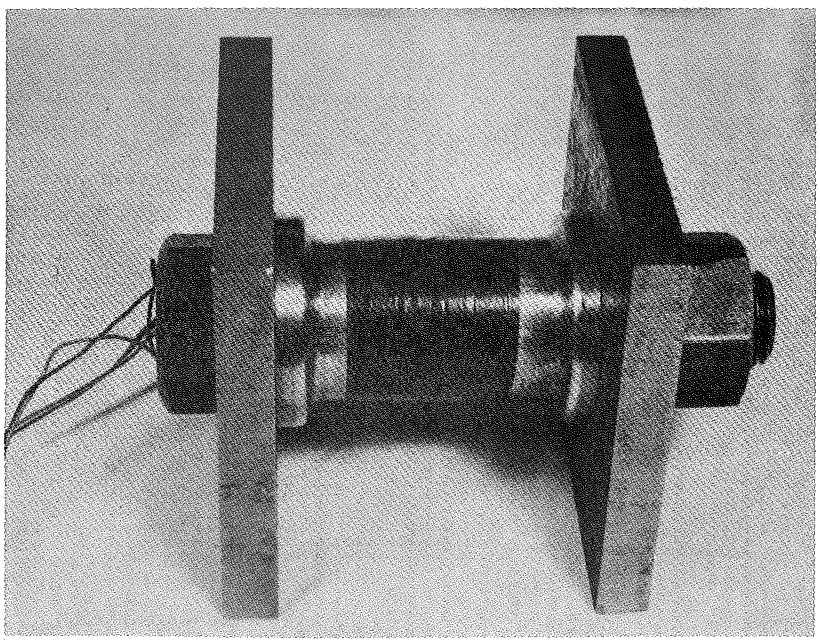


FIG. 11. Bolt in Load Cell

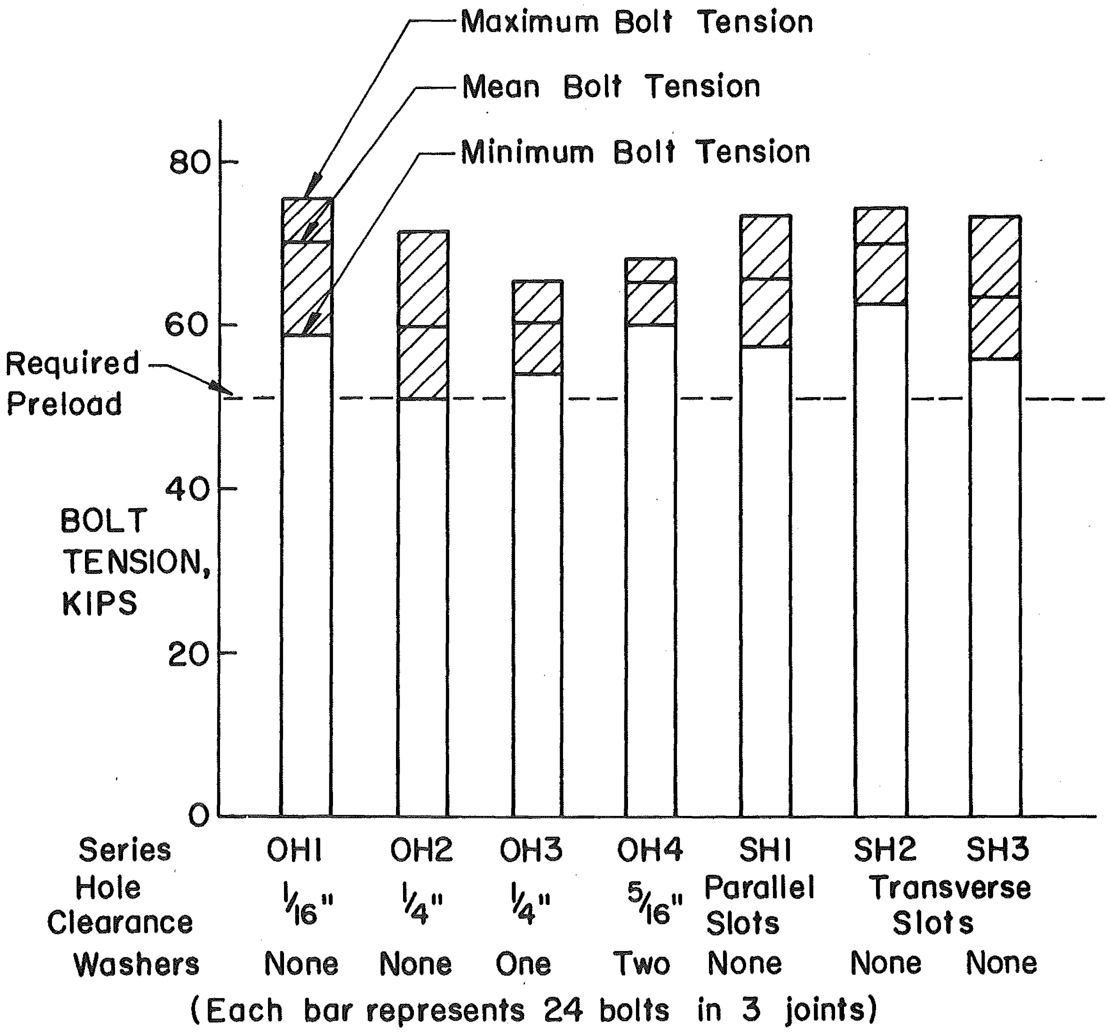


FIG. 12. The Range of Bolt Tensions for all Joints Tested

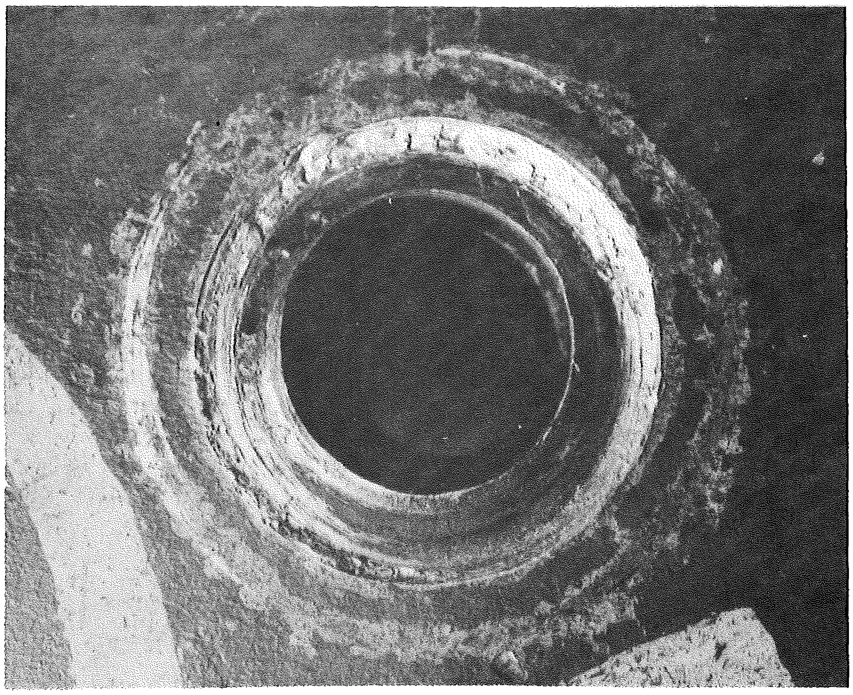


FIG. 13. Galling of Plate Under Turned Element - Joint OH1-2 (1/16-in Clearance)

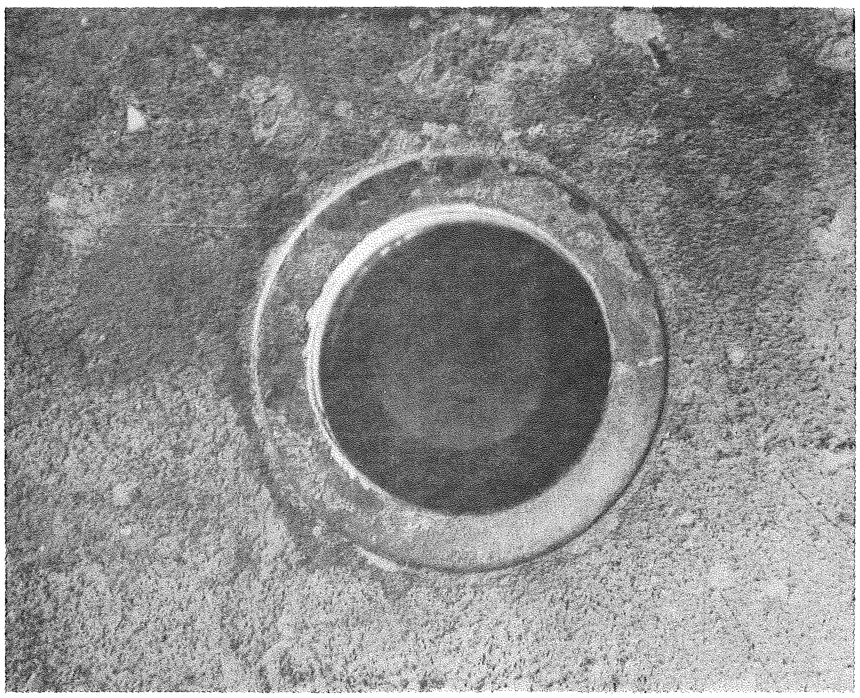


FIG. 14. Depression Under Bolt Head - Joint OH1-2

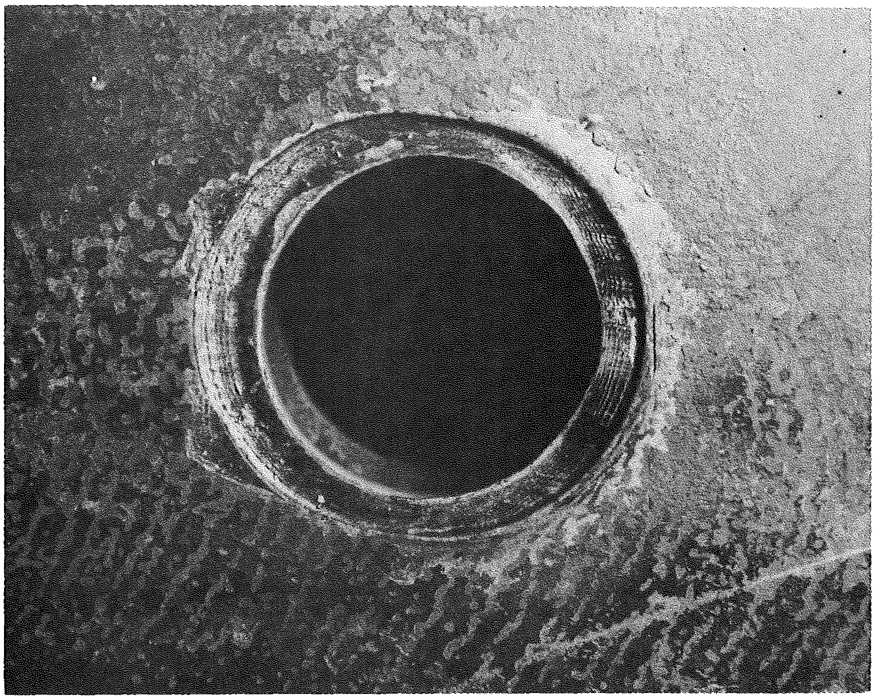


FIG. 15. Depression Under Bolt Head - Joint OH2-1

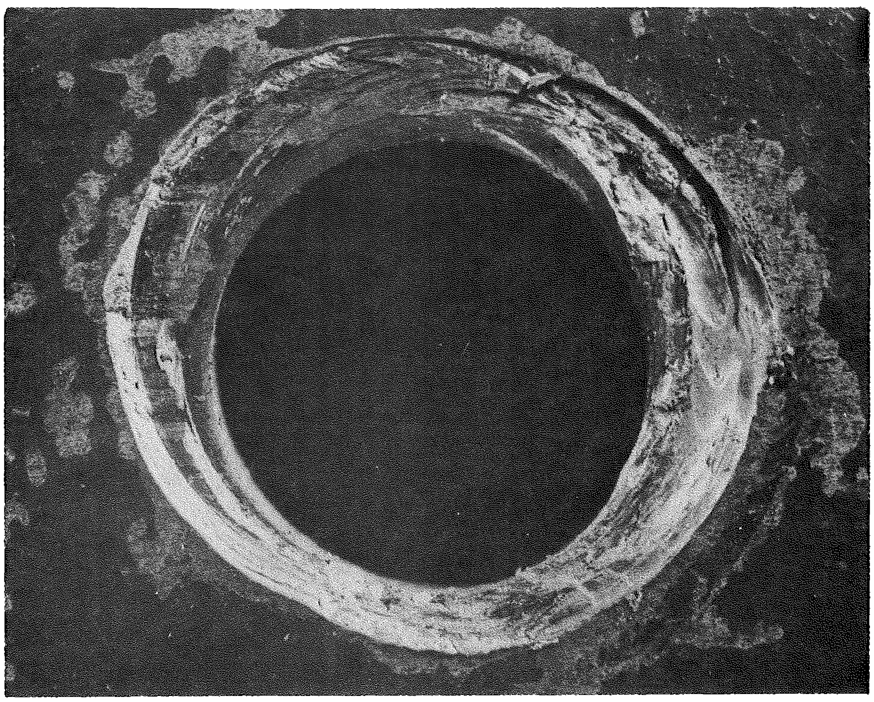


FIG. 16. Severe Galling of Plate Under Turned Element - Joint OH2-1
(1/4-in Clearance, No Washer)

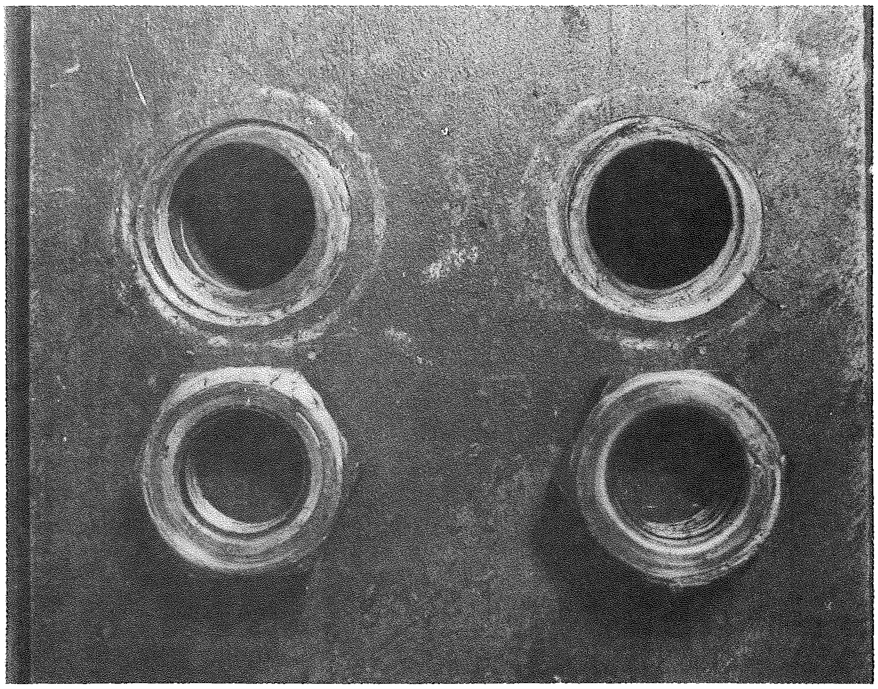


FIG. 17. Severe Galling of Plate and Bolts - Joint OH2-1

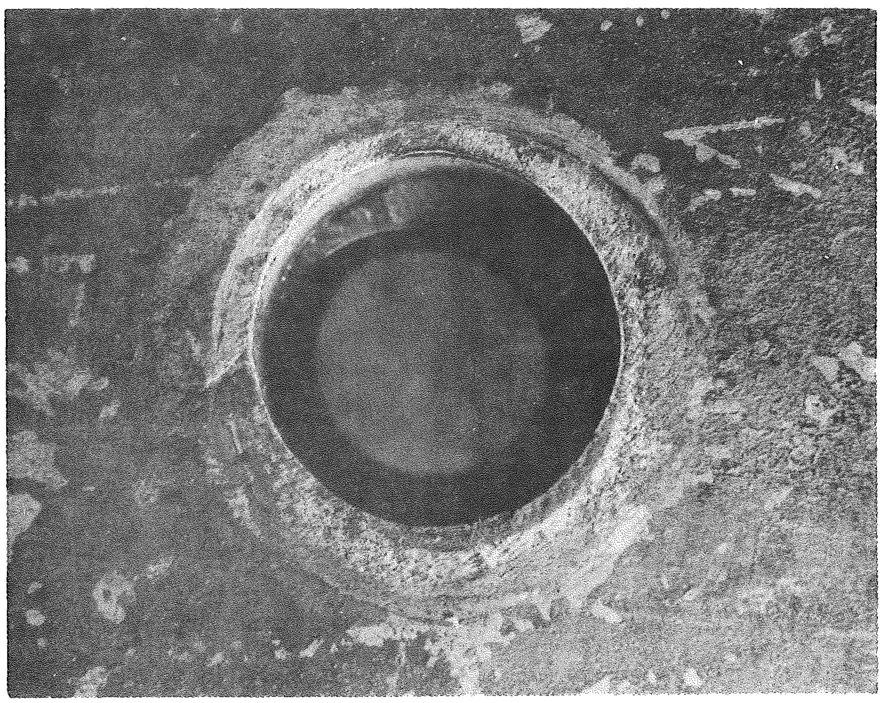


FIG. 18. Plate Area Under Turned Element Where a Washer Was Used - Joint OH3-2 (1/4-in Clearance)

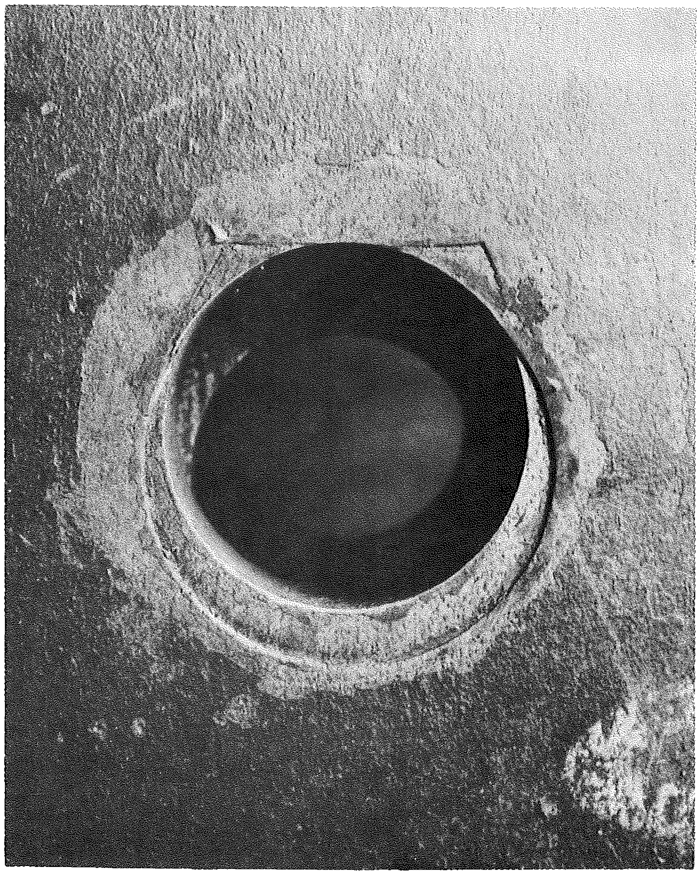


FIG. 19. Depression Under Bolt Head - Joint OH4-2

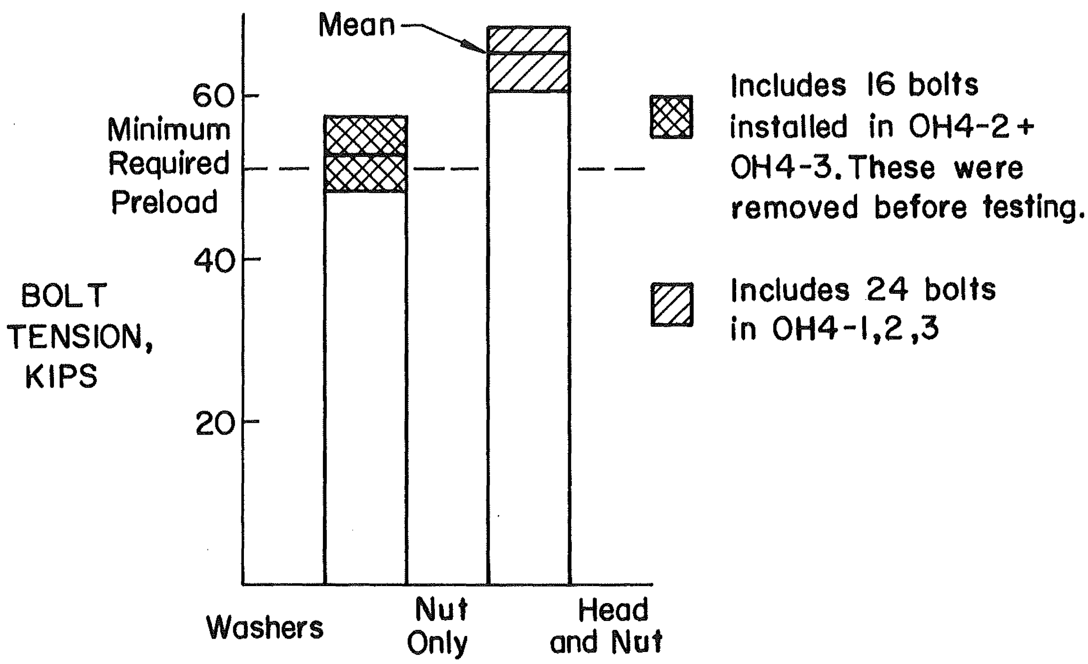


FIG. 20. Bolt Tension for OH4 Joints

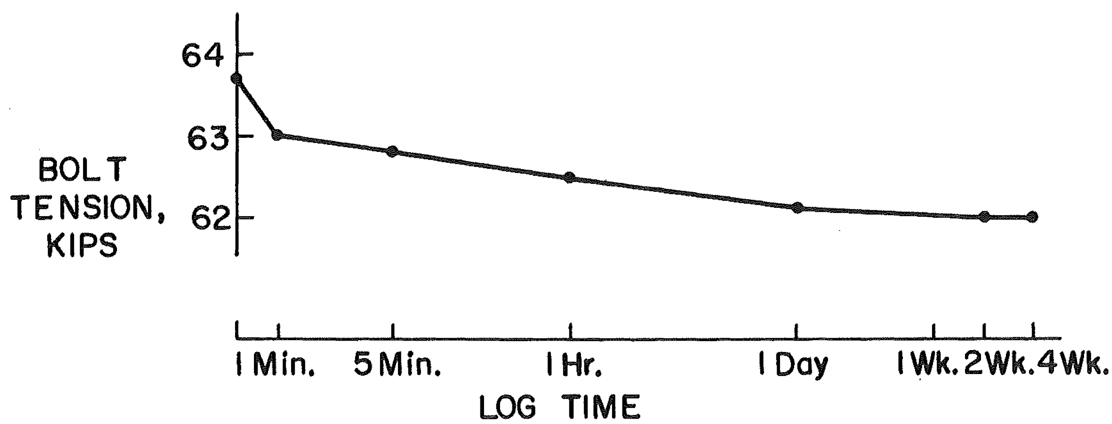


FIG. 21. Time-Tension Relationship of Bolt XB-29 in Joint OH1-2

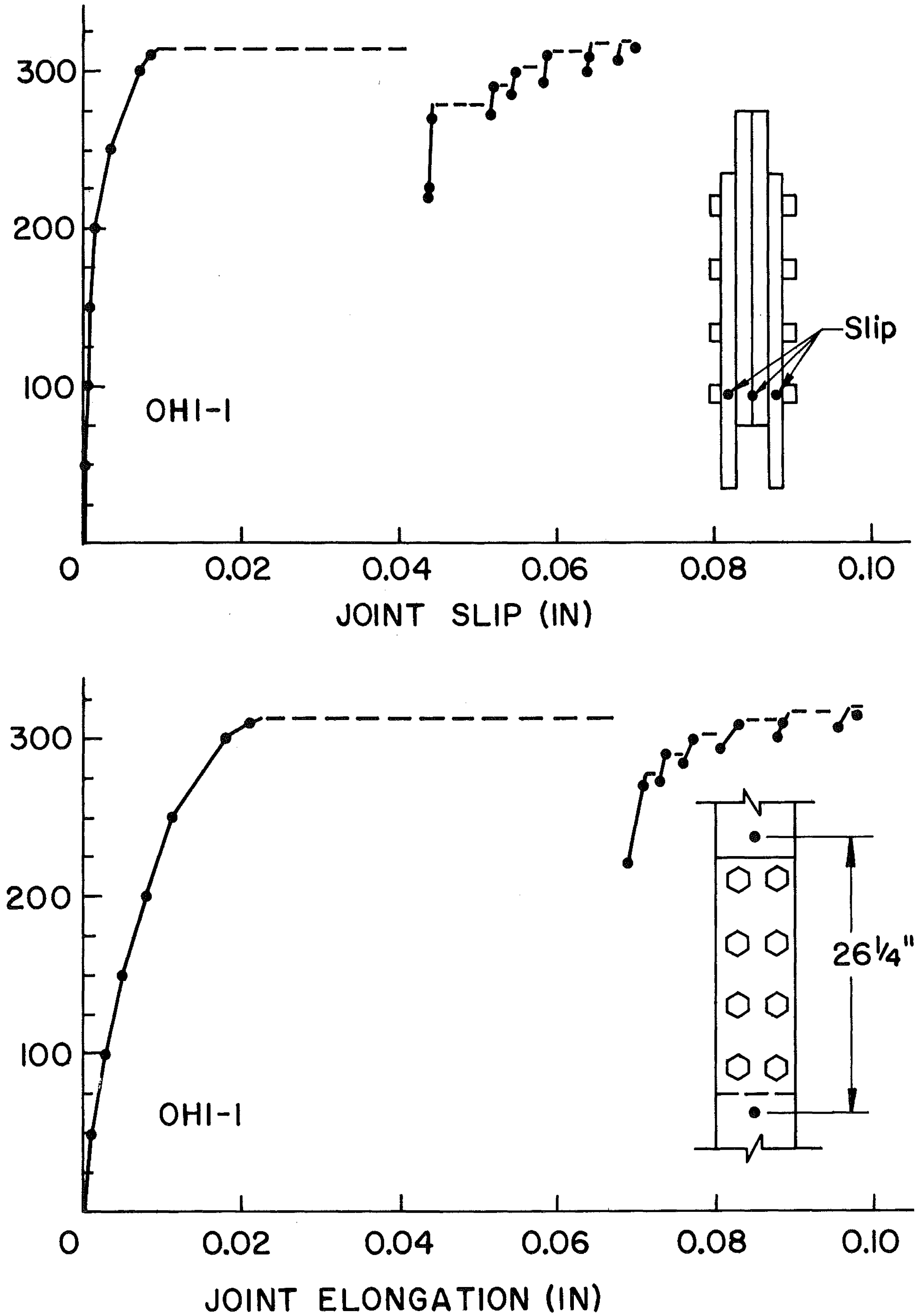


FIG. 22. Joint Slip and Elongation of Joint OH1-1

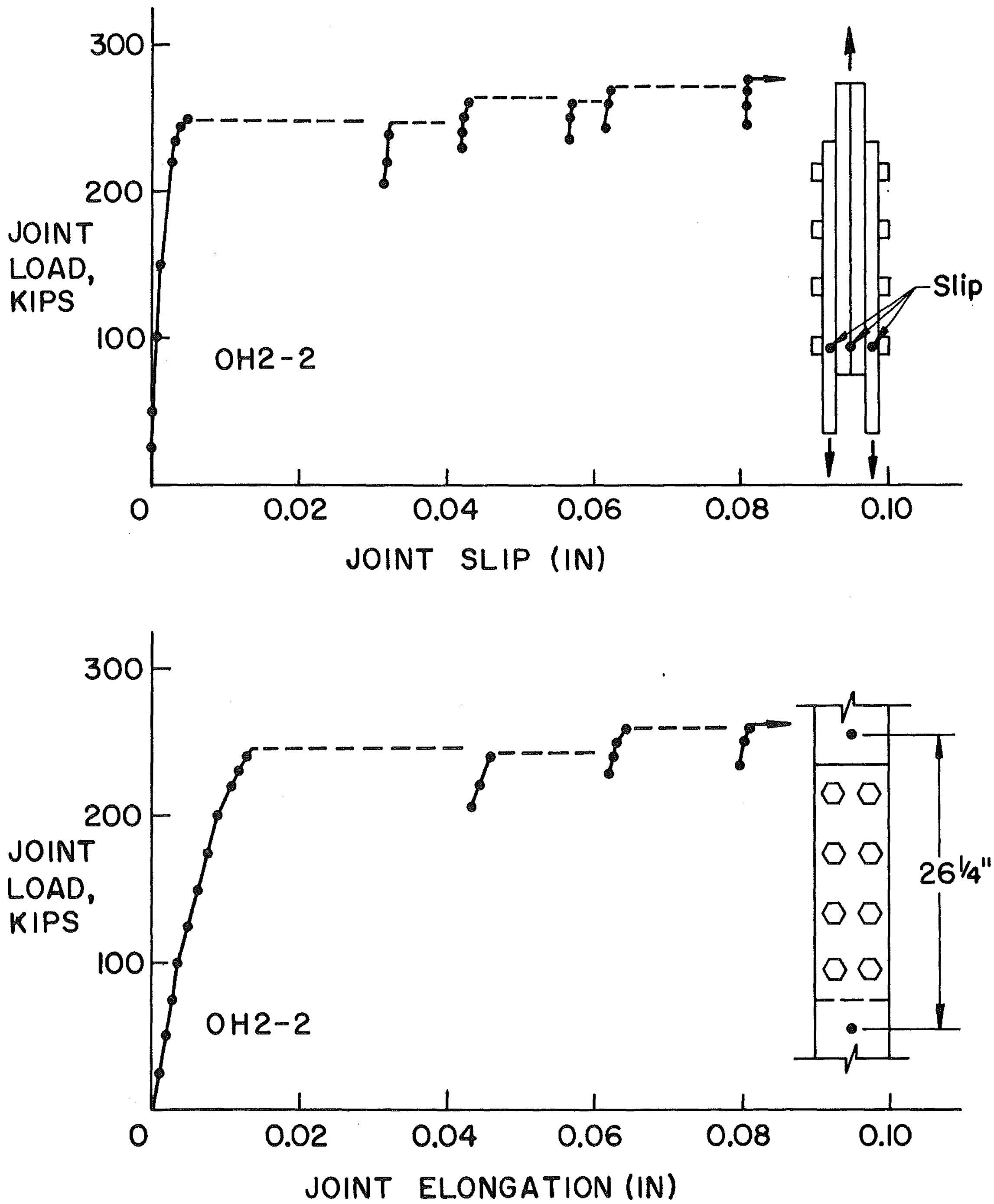
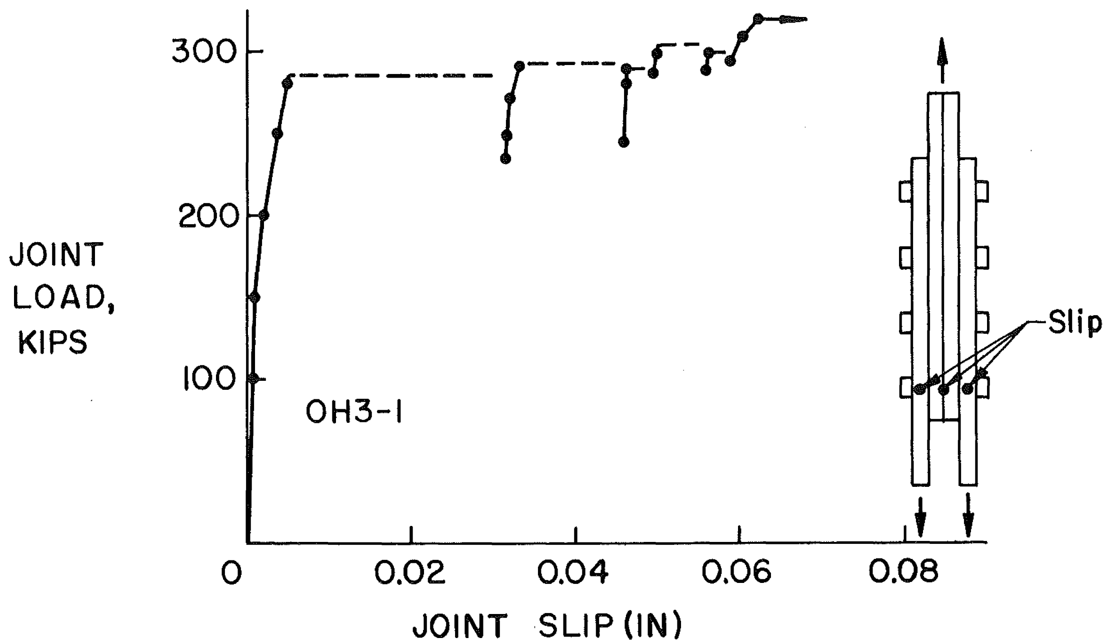


FIG. 23. Joint Slip and Elongation of Joint OH2-2



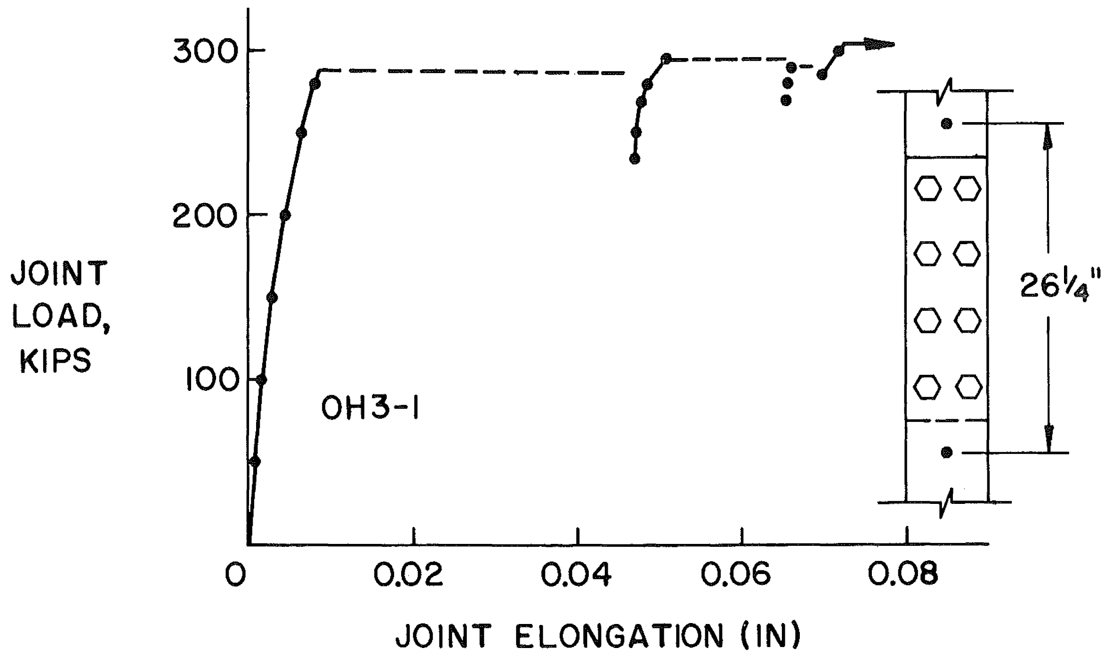


FIG. 24. Joint Slip and Elongation of Joint OH3-1

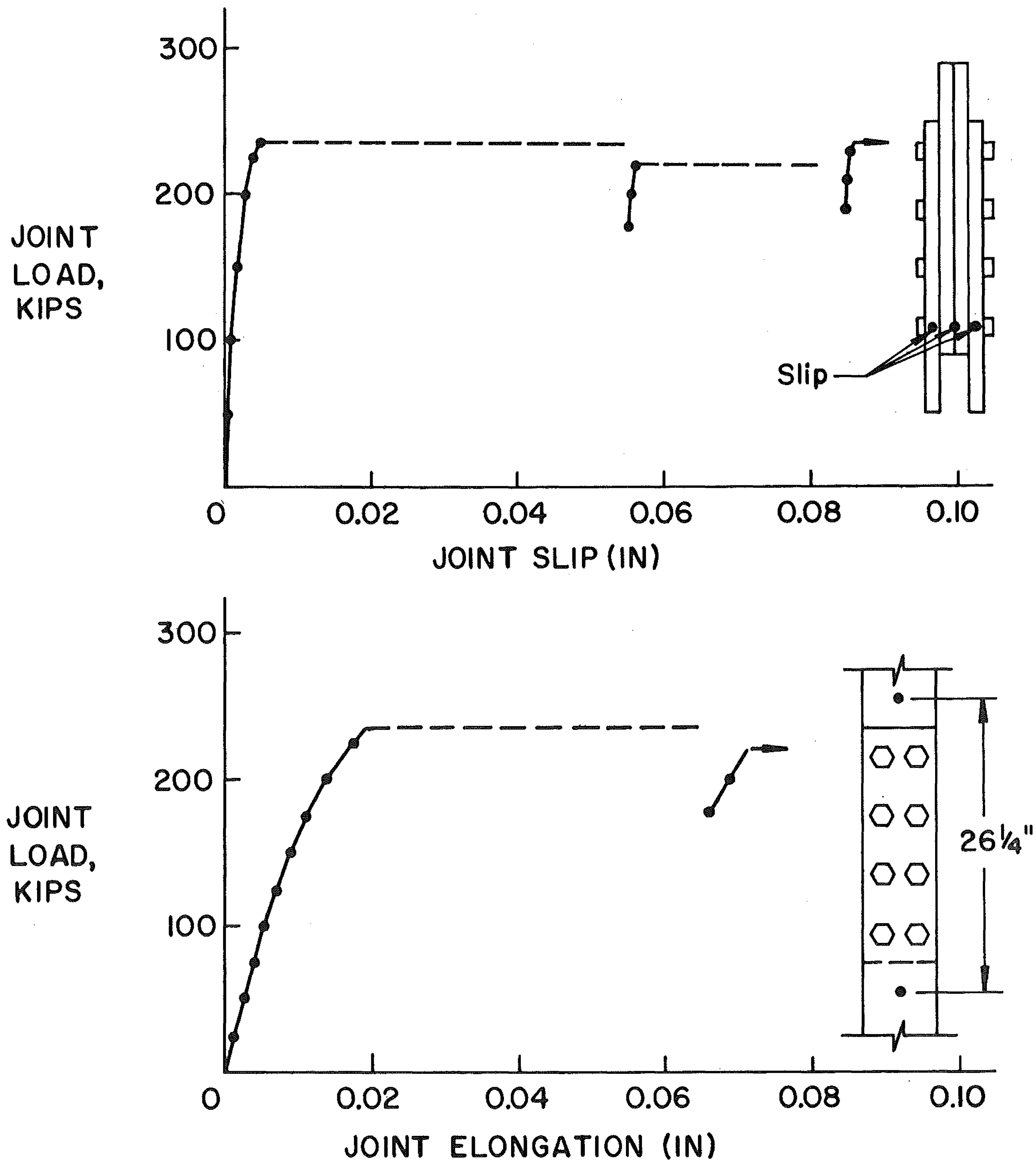


FIG. 25. Joint Slip and Elongation of Joint OH4-3

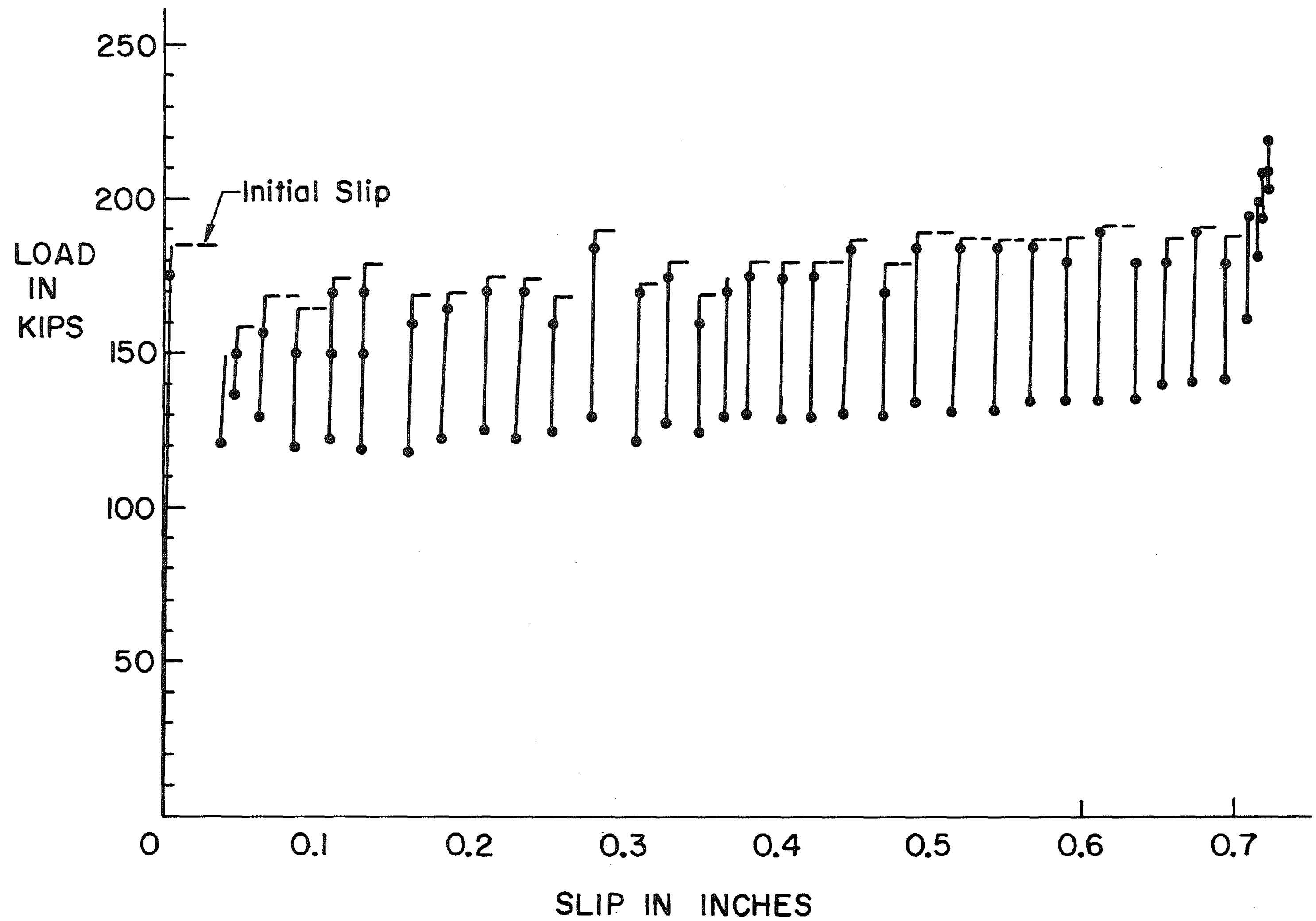


FIG. 26. Load-Slip Diagram of Joint SH1-1

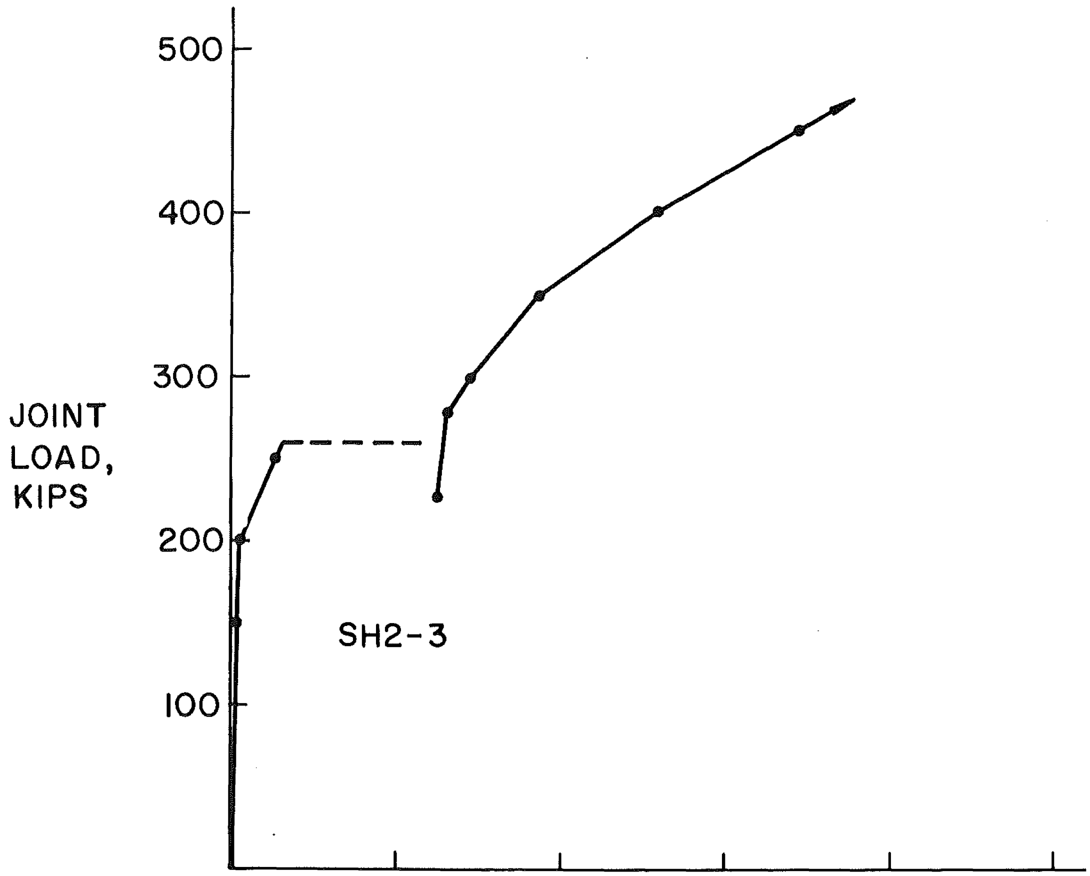


FIG. 27. Load-Slip Relationship of Joint SH2-3

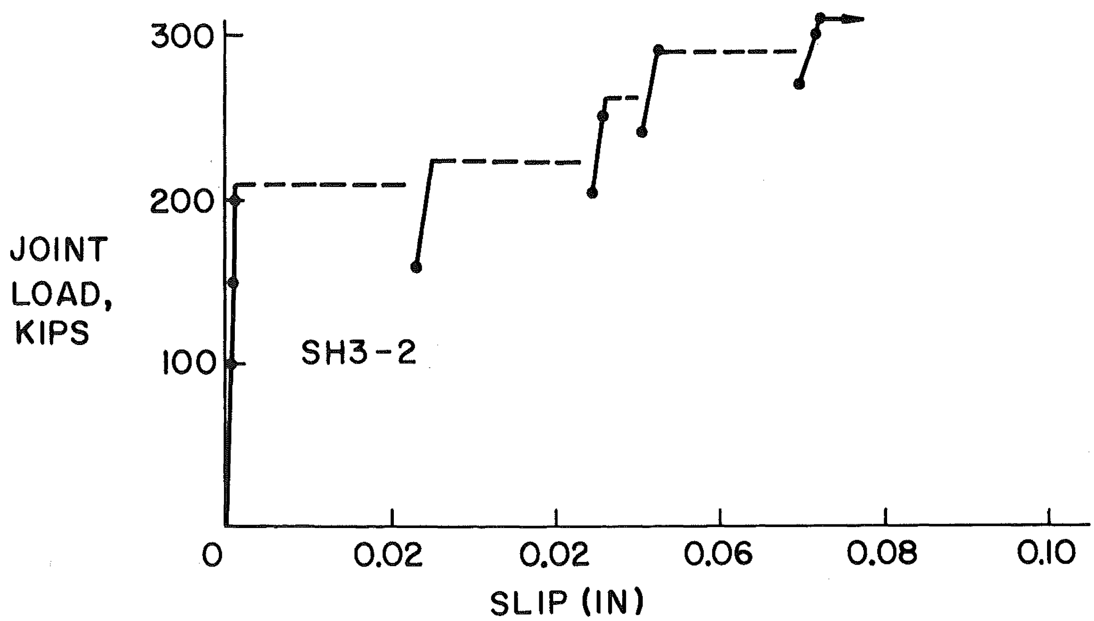


FIG. 28. Load-Slip Relationship of Joint SH3-2

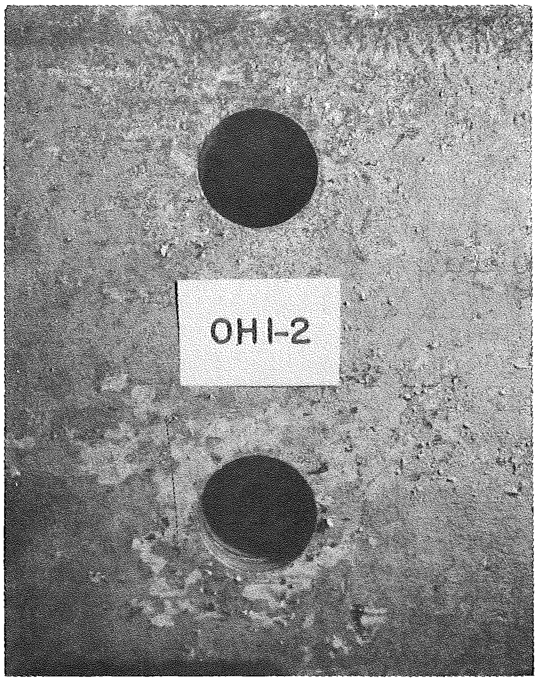


FIG. 29. Faying Surface Damage of OH1 Joint (1/16-in Clearance)

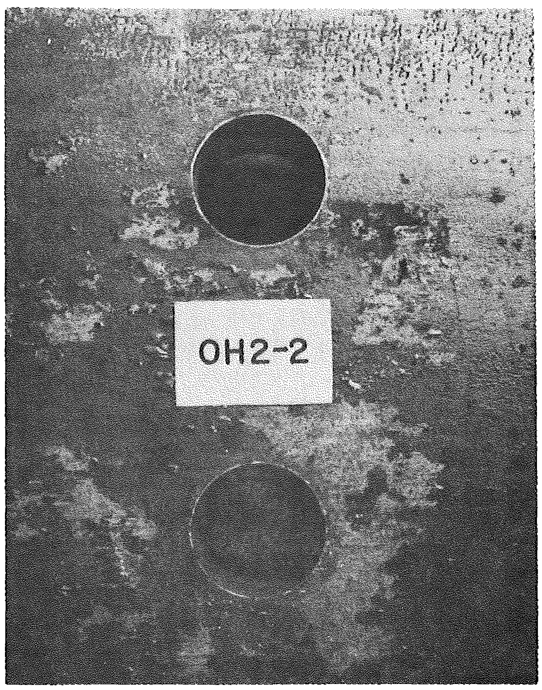


FIG. 30. Faying Surface Damage of OH2 Joint (1/4-in Clearance)

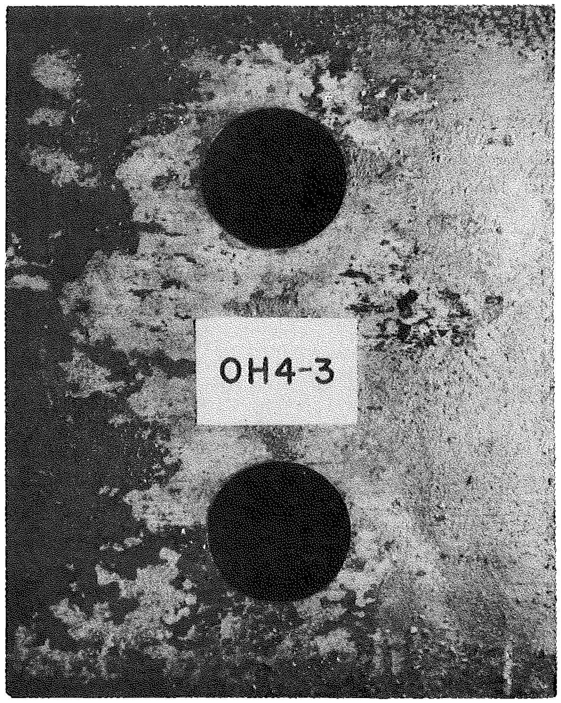


FIG. 31. Faying Surface Damage of OH4 Joint (5/16-in Clearance)

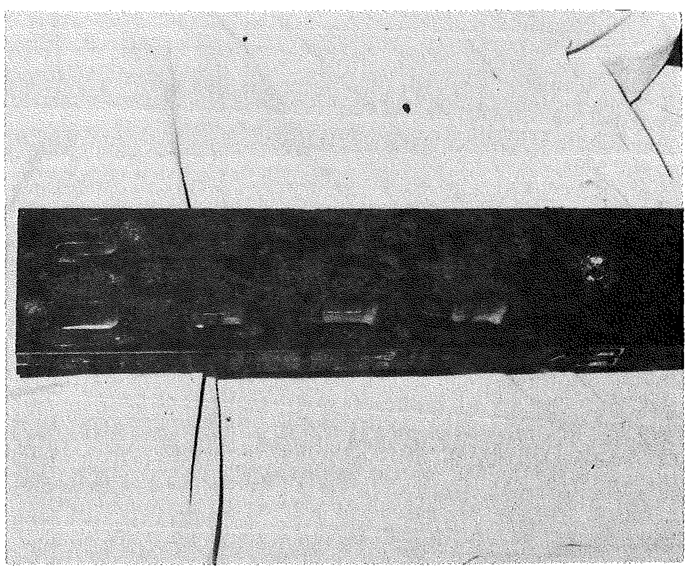


FIG. 32. Faying Surface Damage of SH1 Joint

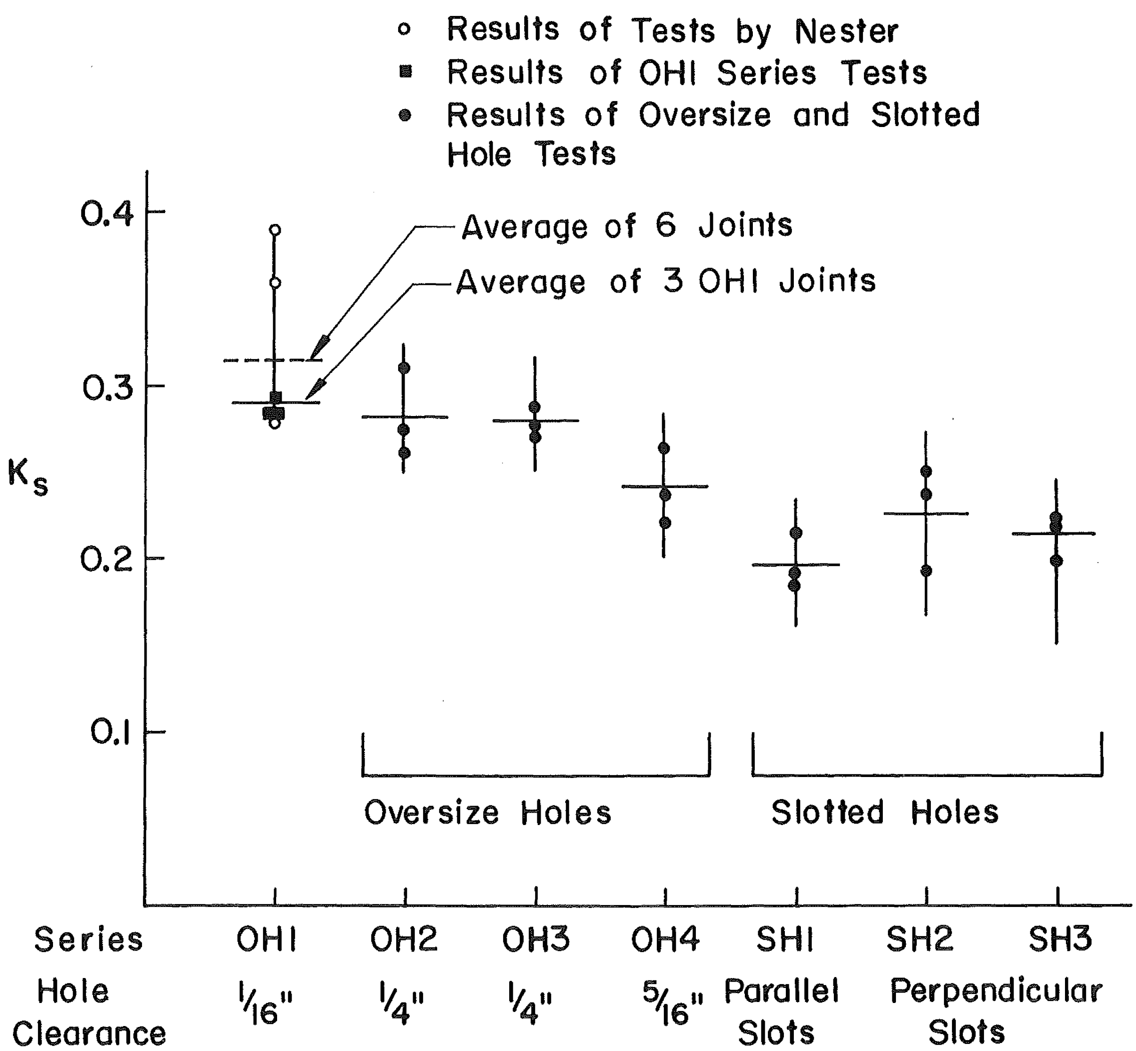


FIG. 33. Comparison of Average Slip Coefficients

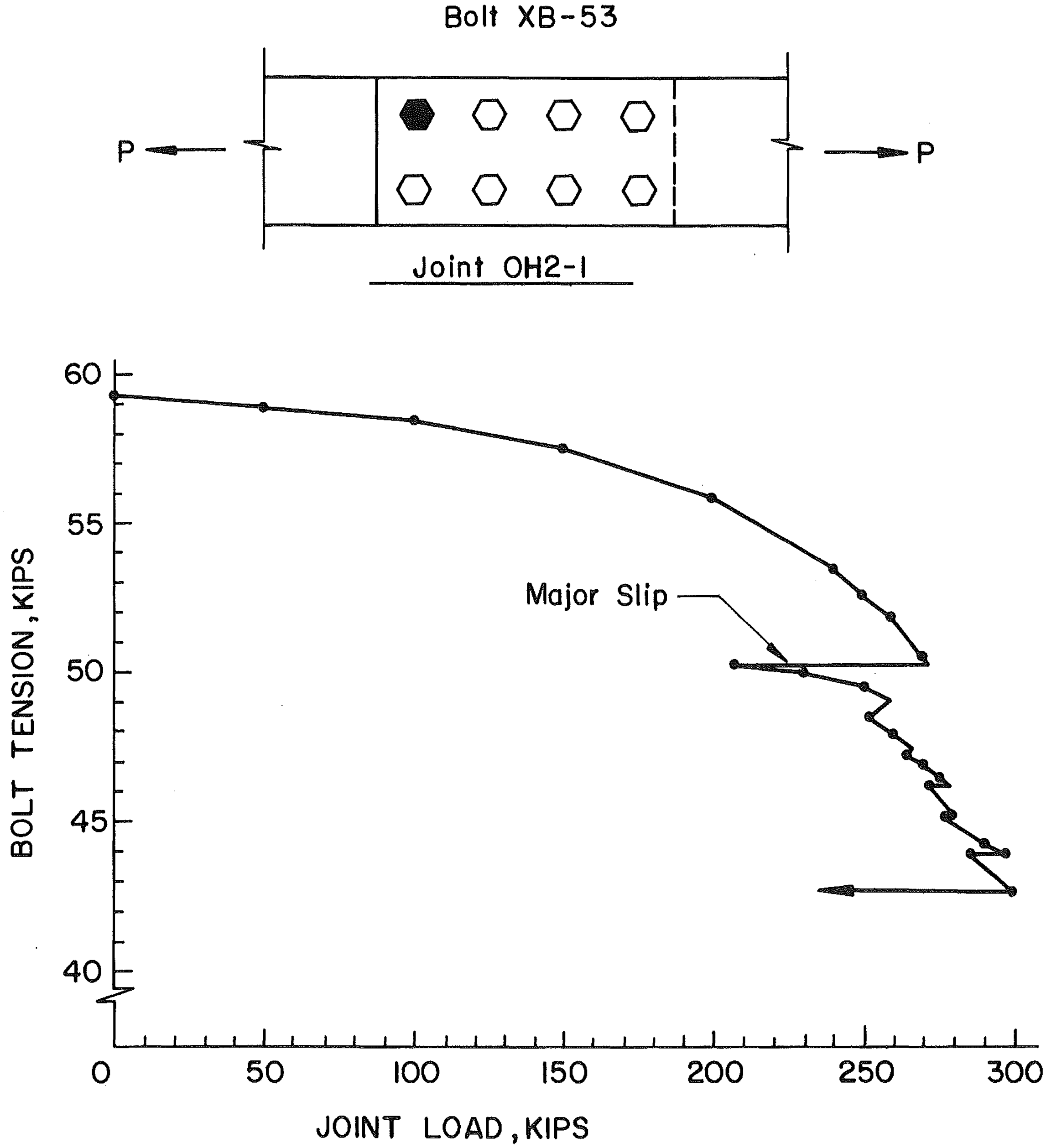


FIG. 34. Changes in Tension During Testing of Bolt XB-53 in Joint OH2-1

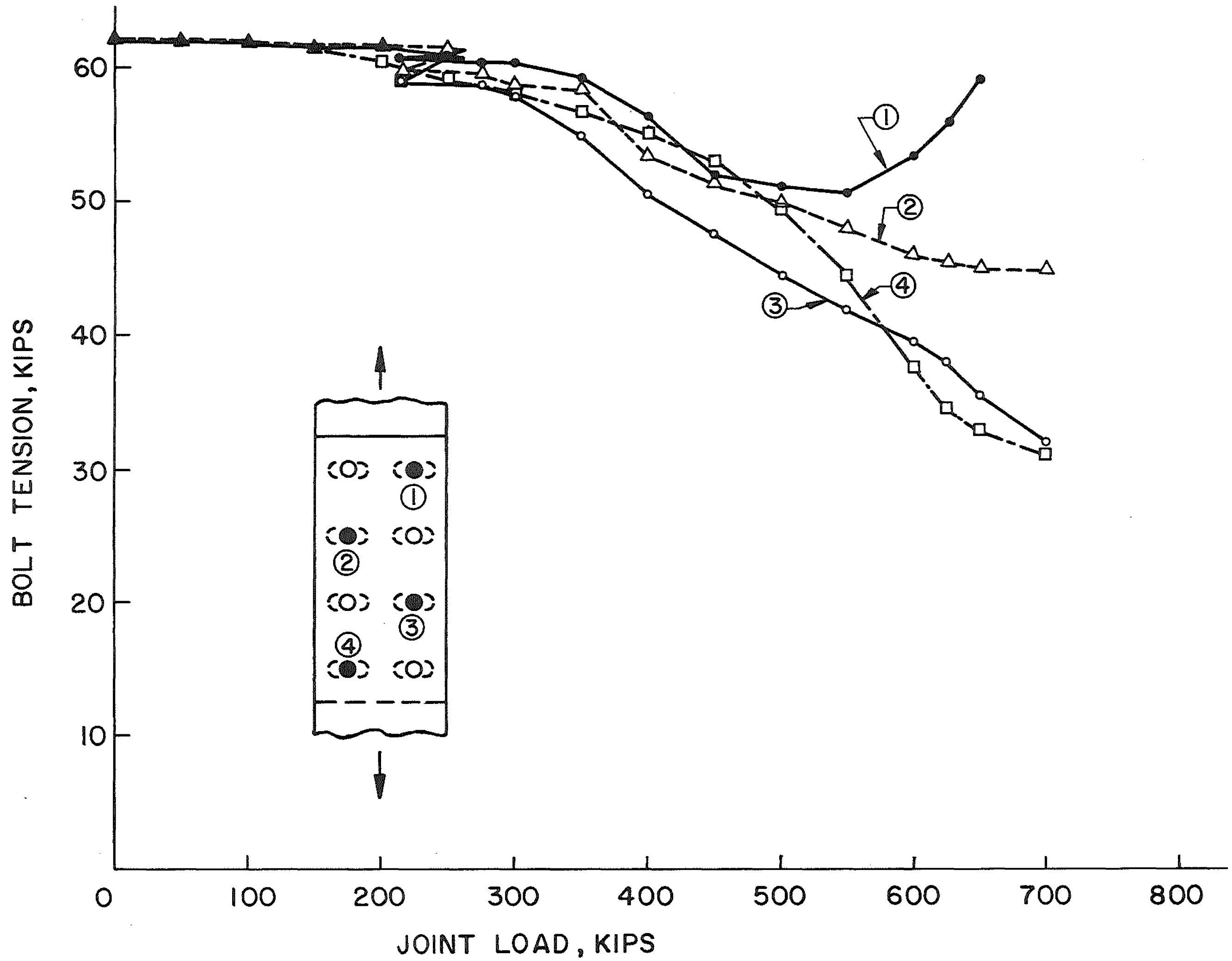


FIG. 35. Bolt Tension - Joint Load Relationship of Joint SH2-3

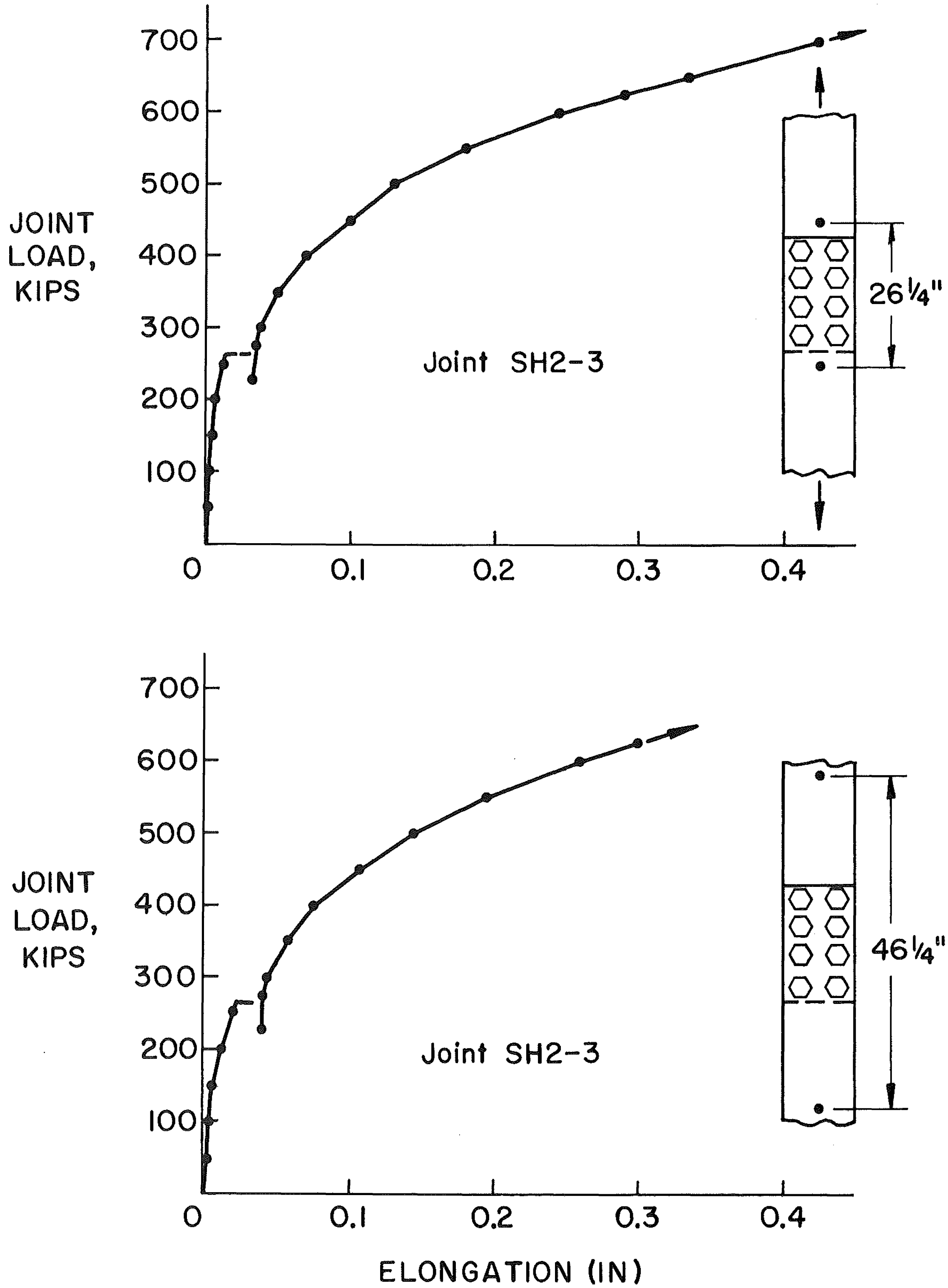


FIG. 36. Load-Joint Elongation and Load-Specimen Elongation of Joint SH2-3

FIG. 37. Deformation of Slotted Holes

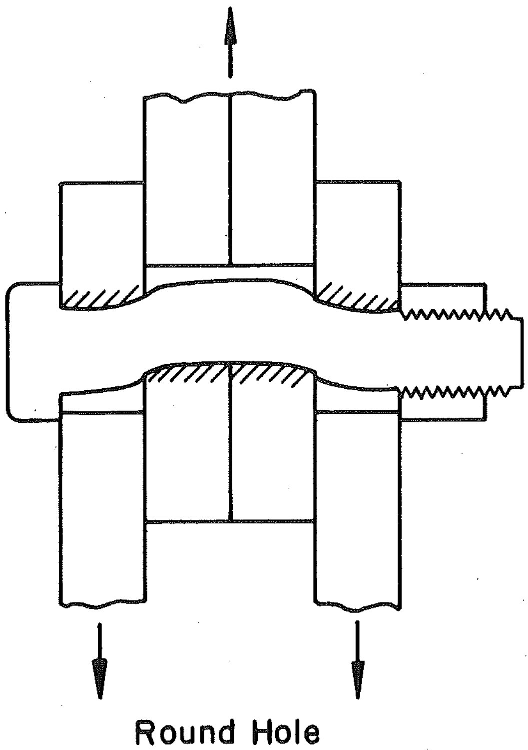


FIG. 38. Comparison of Bolt and Plate Deformations

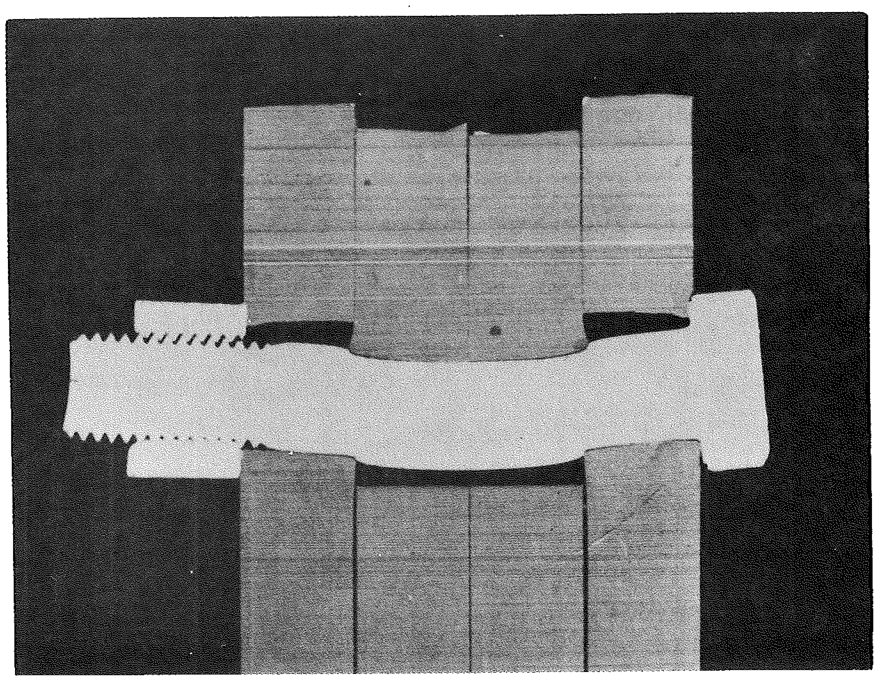


FIG. 39. Deformed Plates and Bolt in Sawed Section of Joint SH3-2

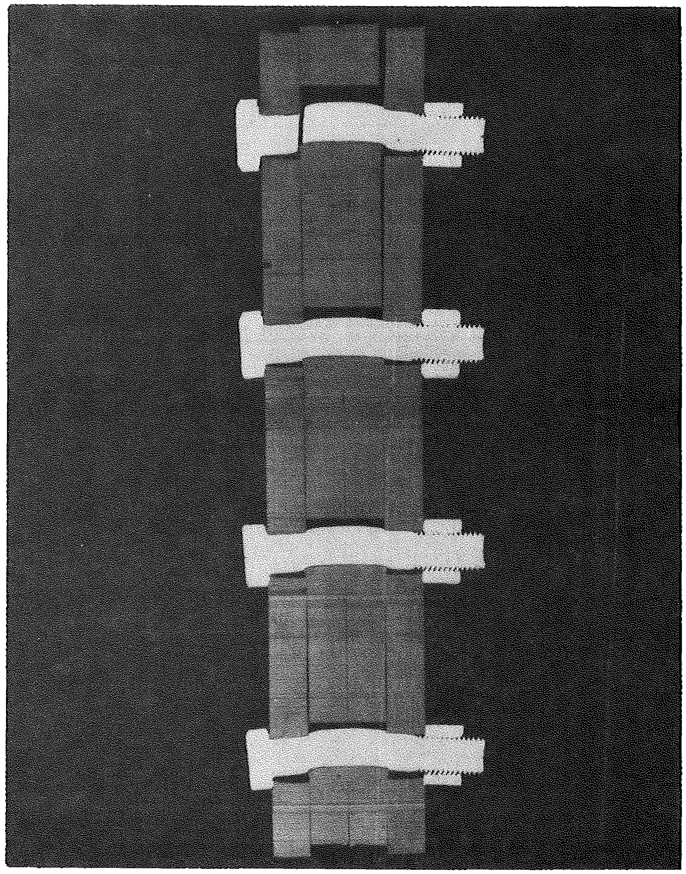


FIG. 40. Sawed Section of Joint SH3-2

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8. VITA

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He enrolled at Newark College of Engineering in 1961 and received his Bachelor of Science in Civil Engineering degree, cum laude, in June 1965. During his undergraduate years he was active in the student chapter of the ASCE and became a member of Chi Epsilon, Tau Beta Pi and Phi Eta Sigma honor fraternities.

In July 1964, he came to Fritz Engineering Laboratory at Lehigh University as a Research Assistant in the Structural Division. He is presently an Engineer-in-Training and an Associate Member of the ASCE.