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BEHAVIOR OF BOLTED JOINTS WITH

OVERSIZE OR SLOTTED HOLES

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ABSTRACT

Twenty-one bolted joints were tested to determine the effect of oversized or 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 parallel and transverse to the line of load were studied. All joints were fabricated from A36 steel plate and fastened by 1 in. A325 bolts. Also studied was 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 co-efficient was observed for the joints with 5/16 in. hole clearance and for those with slotted holes. Slotted holes perpendicular to the line of load did not decrease the ultimate strength of the joints.

ACKNOWLEDGMENTS

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 of joint, slip constitutes failure, and working loads must be resisted by friction between the connected parts with a reasonable factor of safety against slip.

Where slip of the bolted joint is not 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, the shearing of the bolts or failure of the connected parts is critical and allowable stresses are based on the ultimate strength of the connection.

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.[1] There are no provisions in the specifications for the use of larger or slotted holes.

Most of the studies on bolted connections have used test joints having holes with a 1/16 inch clearance. There is a need to evaluate the performance of bolted connections with a greater amount of oversize because 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.[2] Both oversize and slotted holes are desirable to permit erection adjustments.

The purpose of this study is to evaluate the effect oversize and slotted holes have on the slip resistance and ultimate strength of bolted joints. The results of this study should provide information on whether joints with oversize or slotted holes function satisfactorily as friction-type or bearing-type connections.

The study is 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 ultimate strength was also observed.

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 noticeable
effect on the performance of the bolts or of the joints.[3] Therefore,
the Research Council on Riveted and Bolted Structural Joints per-
mitted a bolt hole clearance of 1/16 in. in their first specifica-
tion issued in 1951.

Hoyer[4] 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[5] 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 oversize holes up to 1/8 in. greater in diameter than the bolt
may cause 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 conducted in Germany since 1954 has shown that high strength bolts lose about 10% of their preload over a two-year period.[6,7] Also, the preload was unaffected by temperature changes.[8] In South Africa, Denkhaus[9] observed that the 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[10] showed bolt relaxations of about 6% after 11 years for bolts tightened to their yield point.

Chesson and Munse[5] 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 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 showed a loss in tension of less than 10% over a period of days.[11]

A study to determine the decrease of the preload in high strength bolts over a period of time was conducted in the Netherlands.[12] 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.[13] 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[14] 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 bolted joints.

3.   TESTING PROGRAM

3.1 Description of Specimens

All twenty-one test specimens were fabricated from 1 in. 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 with holes of varying amounts of oversize and three specimens with 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 according to hole size 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. 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 was identical for both groups of joints. 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 enlarged to 1-5/16 in. when 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. Slotted holes located in outside plies would normally be covered with large washers which would cause these plies to act as enclosed plates similar to the test joints. 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 (SH1) contained slots placed parallel to the line of load as indicated in Fig. 3. These were designed as friction-type joints and 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 had slots placed perpendicular to the line of load as shown in Fig. 4. Three of these joints, designated SH2, were proportioned with currently-used allowable stresses and failure was expected to occur by 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 shearing of the bolts. Earlier experimental and theoretical studies

had shown that this would occur if net section area was 36% greater than bolt shear area.

3.2 Plate Properties

The A36 steel plate used for the specimens was purposely ordered at minimum strength. The plates, furnished from the same heat, 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 cut from this piece 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.

Fifteen standard bar tensile coupons were tested. The mean static yield stress of the plates was 29.3 ksi with a standard deviation of 0.6 ksi. The mean tensile strength was 61.0 ksi and its standard deviation was 0.7 ksi.

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, two different bolt lengths were required. Joints without washers used 5-1/4 in. bolts; joints with washers used 5-3/4 in. bolts.

Representative samples of bolts from each lot were calibrated in both direct tension and torque tension to determine their properties. Three bolts from each lot were chosen at random for each calibration. All of the calibrated bolts satisfied the minimum proof load and ultimate load requirements specified by the ASTM. 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. Since the bolts were held at the same grip when tested as existed in the joints, the load-elongation curves used in the torqued tension calibration tests were used to determine the tension in the bolts installed in the joints.

3.4 Fabrication and Assembly of Joints

The test joints were fabricated by a local steel fabricator. 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 then 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 installed either 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 the three with hole diameters of 1-5/16 in., the bolt tension varied from the required

minimum tension to 50% above 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, only half of the bolts
failed to achieve proof load after 1/2 turn of nut. The bolts
were removed and all three joints were bolted with washers placed
under both the heads and the nuts.

3.5 Instrumentation of Joints and Bolts

All of the specimens were instrumented to record their
performance during testing, including 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 tack
welded to the lap plates in line with the tabs. Thus slip move-
ment 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 locat-
ed on the center line of the joints, the top points on both faces
of the main plate and the bottom points 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 re-
lative movement of the studs by means of a sliding rod arrange-
ment.

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 curva-
ture 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.

It was discovered during the direct tension calibrations
that the shanks for 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. 5.

Since the gaged portion remained elastic, it would not
be so 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.

Four gaged bolts were used in each of six of the bolted joints: OH1-1 and OH1-2 (1-1/16 in. diam.); OH2-1 (1-1/4 in. dia., 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). The bolts were arranged in a staggered pattern as shown in Fig. 6.

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 was 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 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 fracture surfaces of the plate failure specimens and faying surfaces were inspected. A sawed section of one of the bolt failure specimens was taken to inspect the condition of the bolts and 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 a result of creep or plastic yield in the threaded portions and elastic recovery caused by plastic flow in the steel plates under the head and nut. Some research has been done on holes with 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, 2-1/2 times the amount in previous studies of 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 and were not disturbed for the duration of the study. Strain gage readings

were taken at the moment each bolt was installed. Subsequent readings were taken at one minute, five minutes, one hour, one week, two weeks, and one month after installation. The strain gage indicator remained 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. 7. 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 horizontally and two placed vertically. 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 be-
havior of a bolt in the test joints were closely approximated.

The bolt to be studied was installed while the load cell
assembly was firmly held in a vise. The bolt gages and the load
cell gages were connected to separate strain gage indicators
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 with
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 pro-
cedure.

The bolts in the OH1 joints (1-1/16 in. hole diameter)
were installed without washers in accordance with the present
specifications for bolted joints, which permit installation
without washers when using the turn-of-nut method. There was
no difficulty in 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 115% and 149% of the
required preload, as shown in Fig. 8. The average bolt
elongations and tensions for each joint are listed in Table 1.
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. 9a. A slight depression occurred under the bolt head,
as shown in Fig. 9b. This nominal amount of damage indicates
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 (i-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 two series are summarized in Table 1. The range of bolt tensions achieved for each series is shown in Fig. 8.

As can be seen in Fig. 8, 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 (130% of proof load). Plate depressions occurring under bolt heads during tightening (Fig. 10a) were greater than those that had occurred in the control joints. This meant that the elongations of the bolts in the 1-1/4 in. holes were smaller than those in the control joints after 1/2 turn-of-nut and hence the bolt tensions were reduced.

Severe galling of both the plate and the nut had occurred during installation in the OH2 series. The damage to the plate is shown in Fig. 10b. For comparison, the surface condition of the plate where washers were used under the nuts in the OH3 series is shown in Fig. 11. Only a slight depression occurred under the washer. It can be seen from Fig. 8 that the

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 without washers was nearly twice as large as the scatter in the bolt tension for the bolts that were installed with washers.

The 1-3/16 in. holes in the OH4 series joints were drilled from the original to 1-5/16 in. after the studies on the slip behavior of the OH2 and OH3 series. The bolts in two of the three OH4 series joints were installed with washers placed under the nuts because of the severe galling that occurred in the OH2 series when 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 removed from the joints. Inspection of the two joints revealed that the bolt heads had recessed severely into the plate around the holes far more than in the OH2 and OH3 series, as shown in Fig. 12. In this instance, the elongations of the bolts were reduced sufficiently so that the bolt preload was less than the required minimum.

All three OH4 joints were then rebolted with washers installed under both the heads and nuts. This time there was no difficulty in achieving bolt tensions above proof load as indicated in Fig. 8. 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.

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 developed under the flat areas of the bolt heads with 1/4 in. clearance holes was the maximum allowable bearing pressure. It 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 2. 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 a 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 to time following installation are listed in Table 3. The time-tension relationship of a typical bolt installed in joint OH1-2 is shown in Fig. 13.

The loss in tension one minute after installation agreed with the one-minute losses reported in a previous investigation,[5] 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 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 4. 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:[15] $K_s = P_s/NT_i$, 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 1. Typical load-slip and load-joint elongation relationships are shown in Figs. 14 and 15.

The load-slip response of the oversize and slotted hole 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 dial movement began to accelerate 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. The 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 oc-
curred at higher loads than the major slip load. The number of
smaller slips increased as the hole diameter increased. The ini-
tial slip did not bring the joint into bearing because of the de-
crease in load caused by the slip. In an actual structure the load
might remain constant and the joint would slip into bearing at the
initial slip.

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 com-
parable to the average slip coefficient of 0.34 obtained by Nester[14]
from a series of bolted connections made from the same heat of steel.
Tests conducted at the University of Washington[16] on A36 steel bolted
joints yielded comparable results.

Investigation of the faying surfaces of the joints indicated
that damage to the mill scale surface was confined mostly 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. Figure 16 shows the mill scale surface
damage near the bolt holes.

The OH2 and OH3 joints with the 1/4 in. hole clearance pro-
vided 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. 16). This also showed that the pressure distribution in these joints was similar to the pressure distribution 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 lower slip resistance. The average slip coefficient for these joints was 0.24. Inspection of the faying surfaces after testing 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 placed parallel to the line of load. These joints also showed lower slip coefficient. The average slip coefficient for the series was 0.20.

The slip behavior of three of the bearing joints (SH2-1, SH2-2 and SH3-1) was different from that of the rest. 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 (0.30-0.50 in.) to be considered 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 also summarized in Table 1. The average slip

coefficients for the SH2 and SH3 series were 0.23 and 0.21, respec-

tively.

The average slip coefficients of all of the joint series

are compared in Fig. 17. It is apparent that the average slip co-

efficient for the OH2 and OH3 series was about the same as the aver-

age 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 coefficient 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.[17]

High frictional forces that are proportional to the contact pressure

and the interlocking of the surface irregularities in these areas con-

stitute 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 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 5a. The load-joint elongation and load-specimen elongation relationship of joint SH2-3 is summarized in Fig. 18.

In all cases, the interior slotted plate failed at the first row of slots. Fig. 19 shows the deformation in the slotted holes of joint SH2-2 at failure.

The ultimate load for all three specimens was roughly 110% of the predicted load based on the coupon tests. This is in agreement with the results of earlier studies conducted on bolted joints with standard round holes.[15]

The three joints of the SH3 series were proportioned so that failure would occur by shearing of the bolts. The geometry of the

joints was based on the assumption that minimum-strength bolts were to be used for the tests. However, the shear strength of the bolts exceeded the plate capacity and joint SH3-1 failed by a tearing of the plate.

A new lot of bolts specified to be of minimum strength was ordered. The bolts were tested in shear jigs with both slotted and round holes. The average shear strength of the bolts in the slotted hole shear jigs was 84.3 ksi while the shear strength in the round hole was 81.3 ksi. This was caused by a ballooning of the plate as the bolt shearing caused deformation on the flat portion of the slot as shown in Fig. 20. This caused a shifting of the shear plane with a resultant increase in the shear area of the bolt shank.

The tests of joints with these bolts are summarized in Table 5b. The deformation of a bolt and the plates of joint SH3-2 are shown in Fig. 21. 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 shown in Fig. 22 shows the deformation of the bolts and of the enclosed plate.

It can thus be concluded that slotted holes in the enclosed plates of a bolted joint do 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.   One-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 control 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 oversize holes or 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.   <u>TABLES AND FIGURES</u>

TABLE 1

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 2

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 3

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 4

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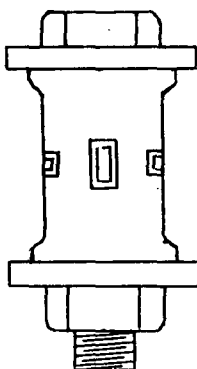
Hole Clearance in.	Initial Bolt Tension, Kips	Loss in Tension, Kips									
		1 Min.		5 Min.		1 Hr.		1 Day		1 Week	
		Bolt	Cell	Bolt	Cell	Bolt	Cell	Bolt	Cell	Bolt	Cell
1/16 in. (Std)	60.0	1.0	0.6	1.3	1.4	1.3	1.9	1.3	2.5	1.3	2.6
1/4 in.	59.5	0.8	0.4	1.3	0.9	1.6	1.3	2.0	1.4	2.3	1.4
5/16 in.	60.7	0.7	0.2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

TABLE 5

Test Results - Bearing Joints

a. 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

b. 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
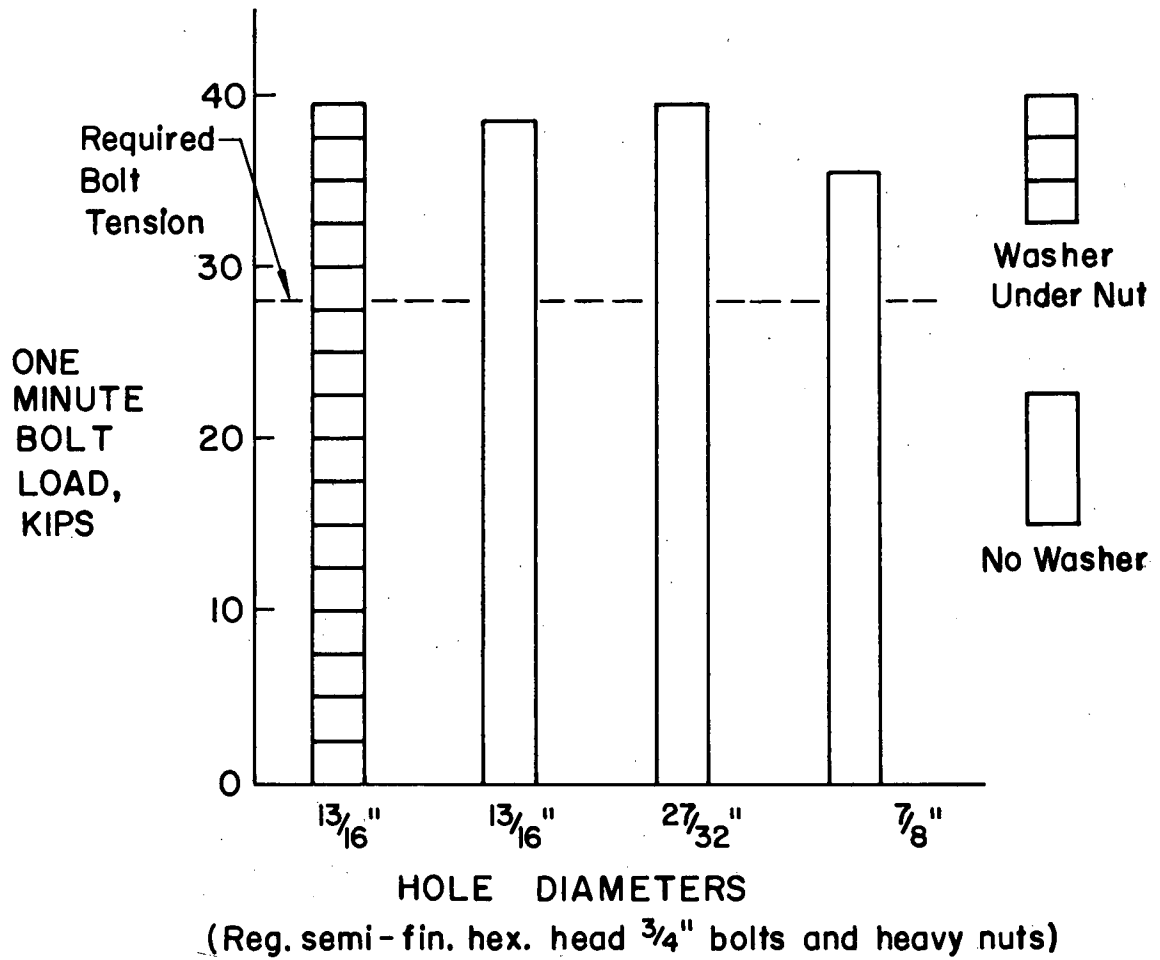
FIG. 1.   Effect of Hole Size on Bolt Tension Induced by Turn-of-Nut
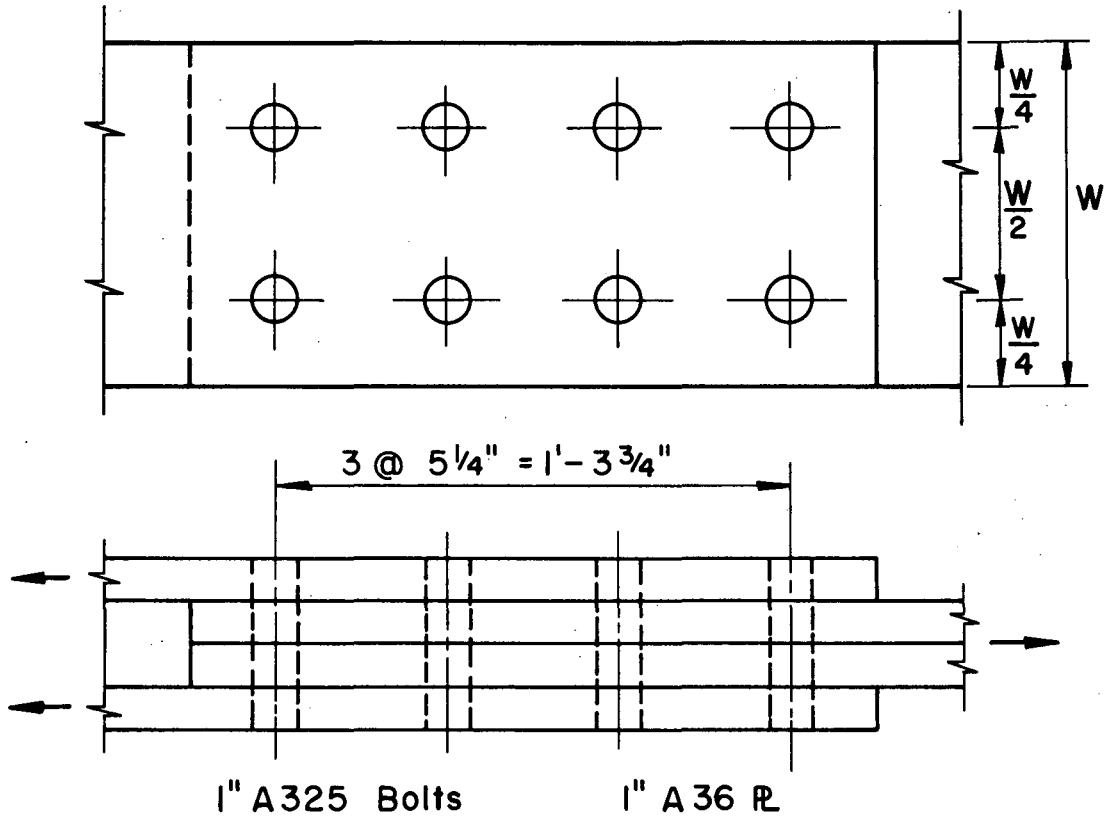
SERIES	NO. TESTED	HOLE DIA.	WIDTH "W"
OHI	3	1 1/16"	6.40"
OH2	3	1 1/4"	6.78"
OH3	3	1 1/4"	6.78"
OH4	3	1 5/16"	6.65"

FIG. 2. Oversize/Hole Test Specimens
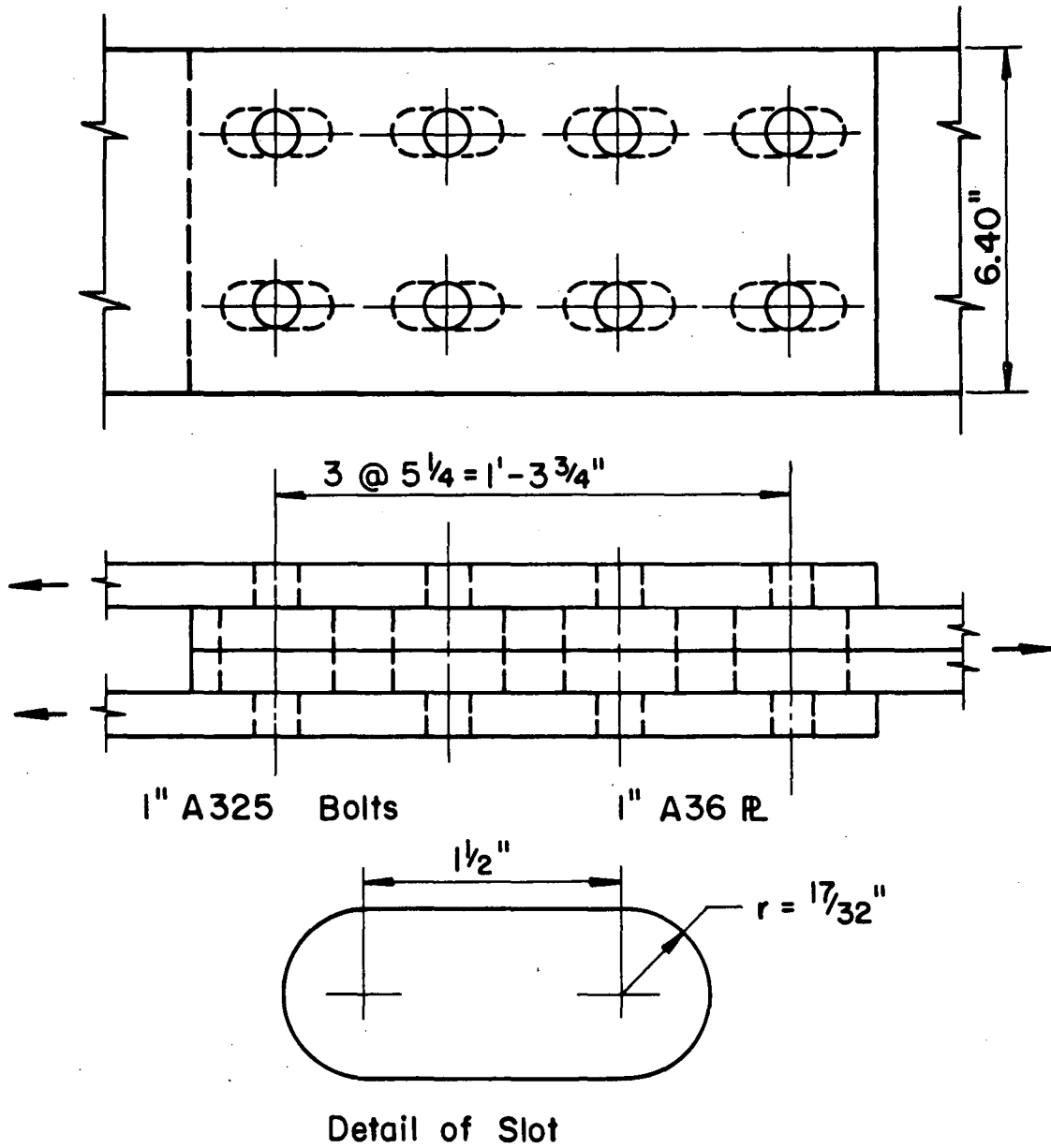
FIG. 3. Test Specimens - Slotted Holes Parallel to the Line of Load
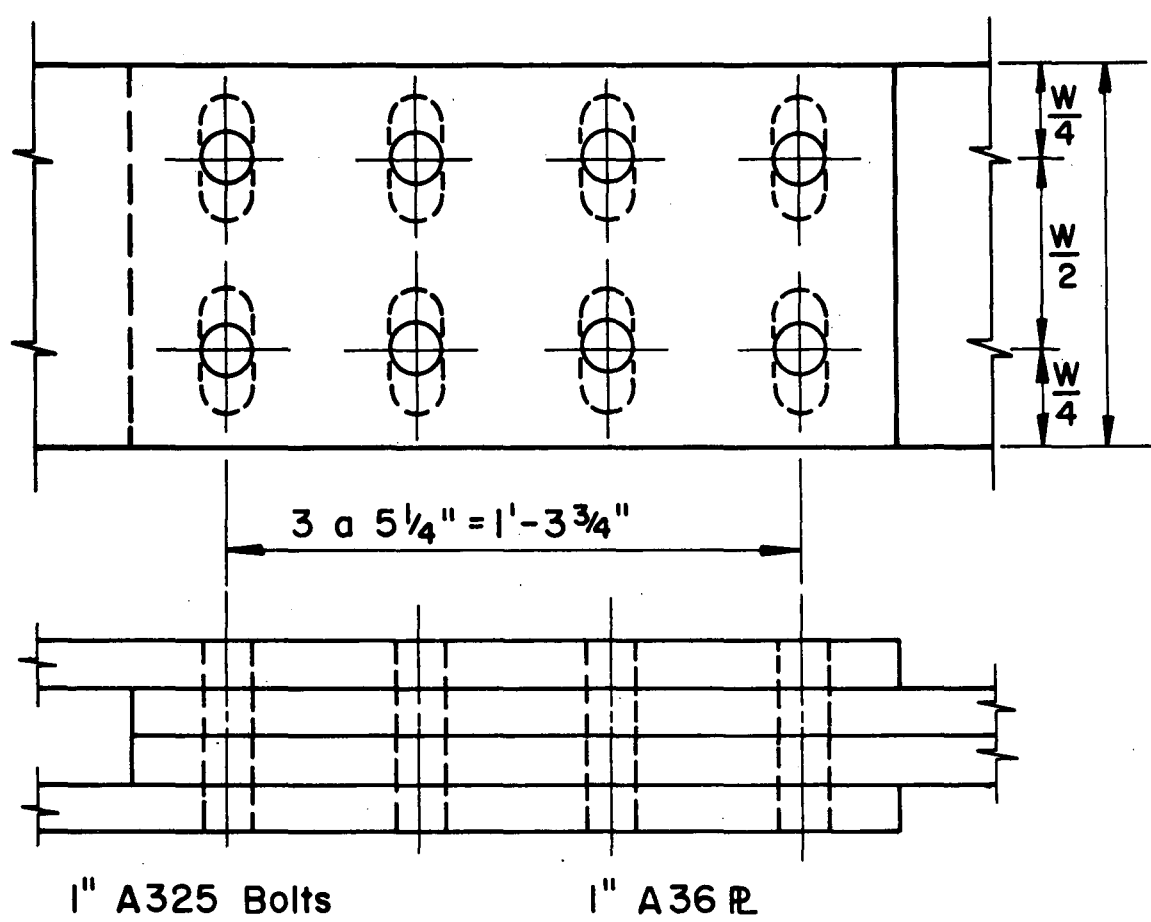
FIG. 4. Test Specimens - Slotted Holes Perpendicular to the Line of Load
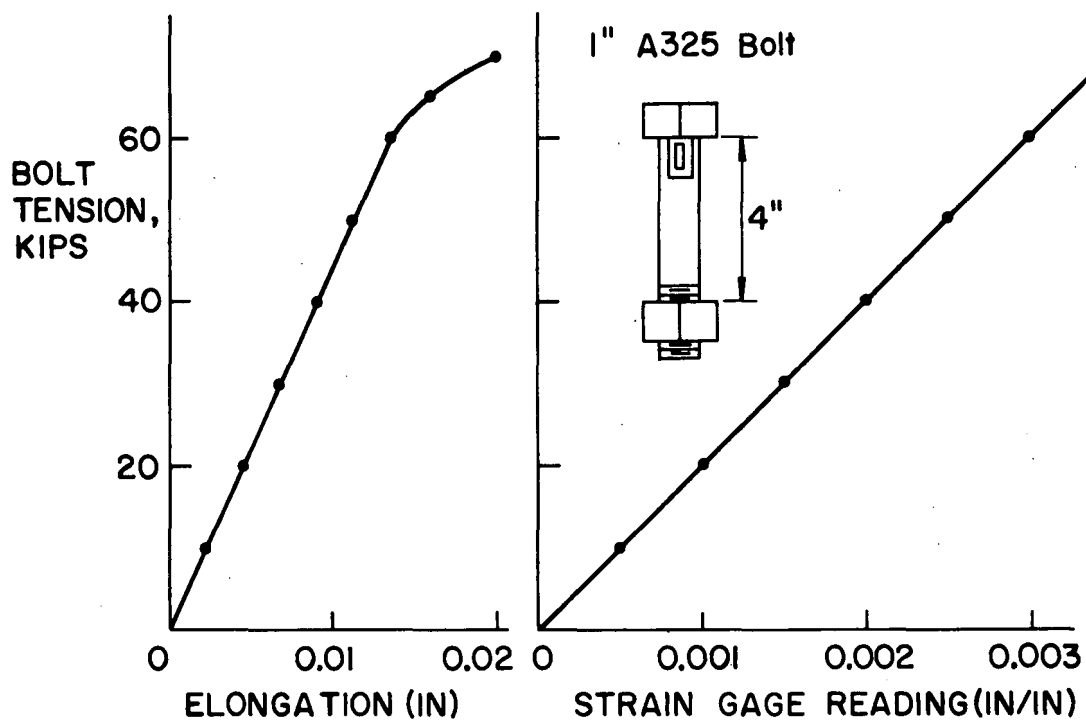
FIG. 5   Calibration of Gaged Bolts
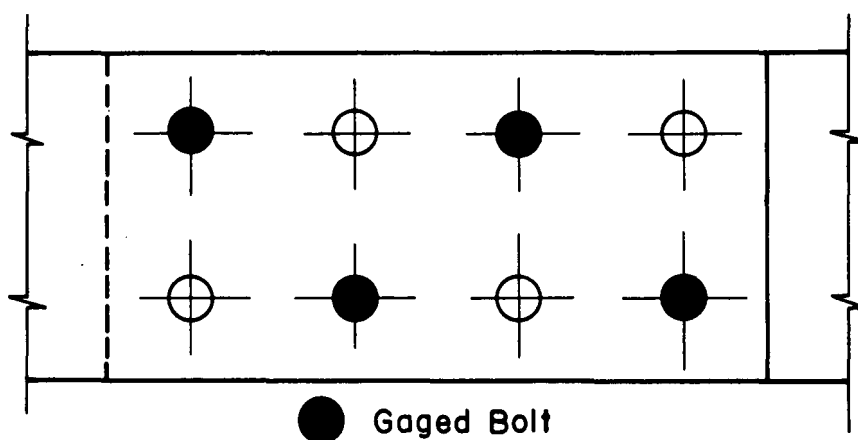
FIG. 6   Location of Gaged Bolts in Joint
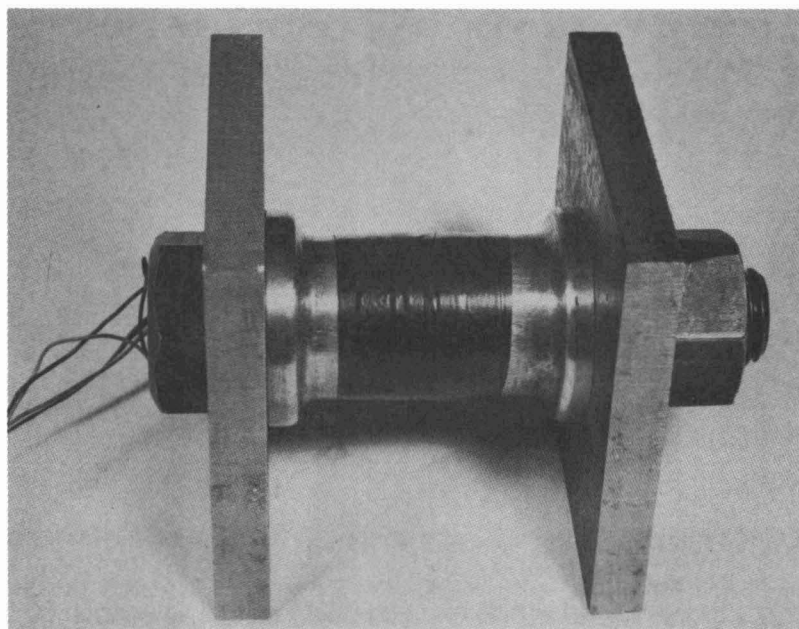
FIG. 7   Bolt in Load Cell
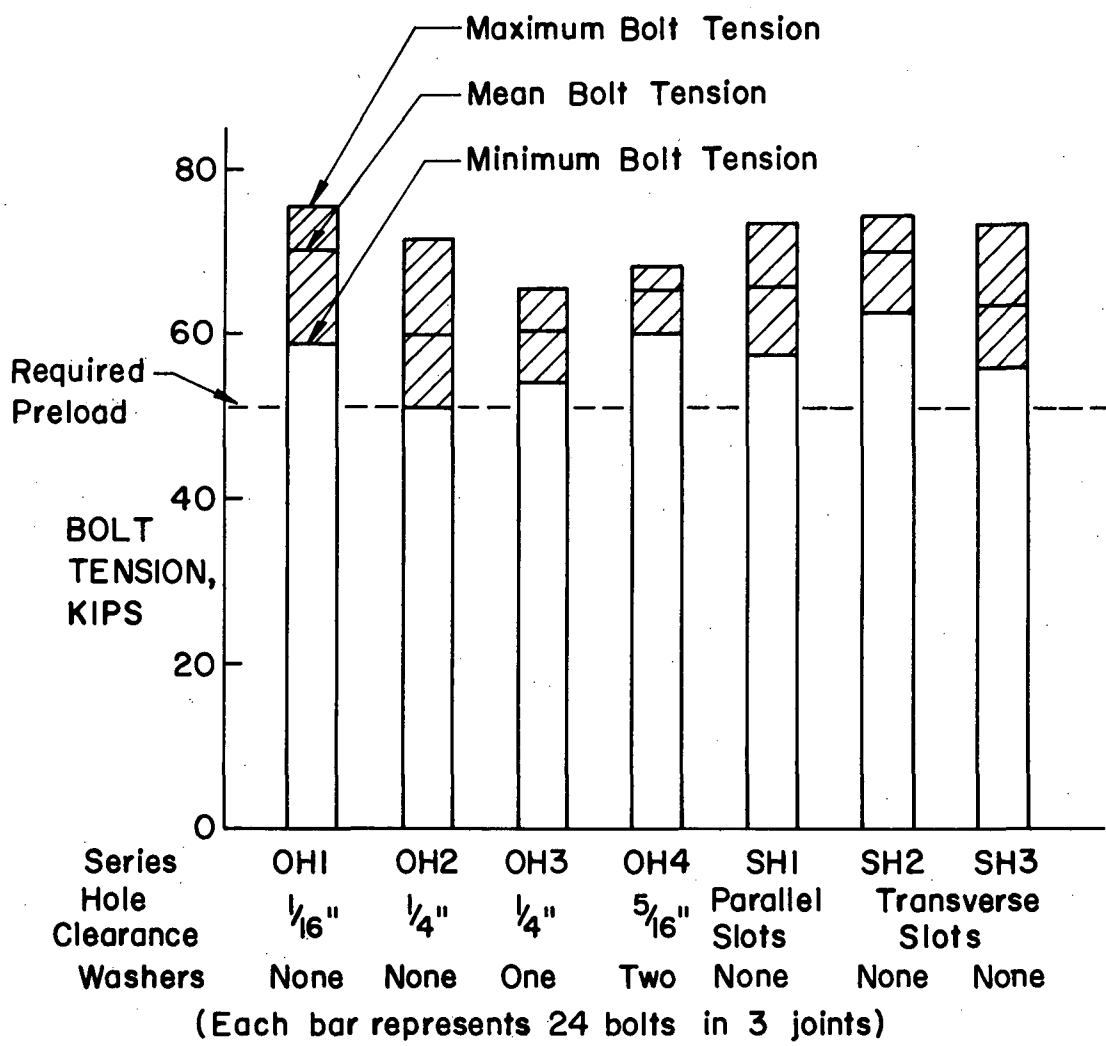
FIG. 8   The Range of Bolt Tensions for all Joints Tested
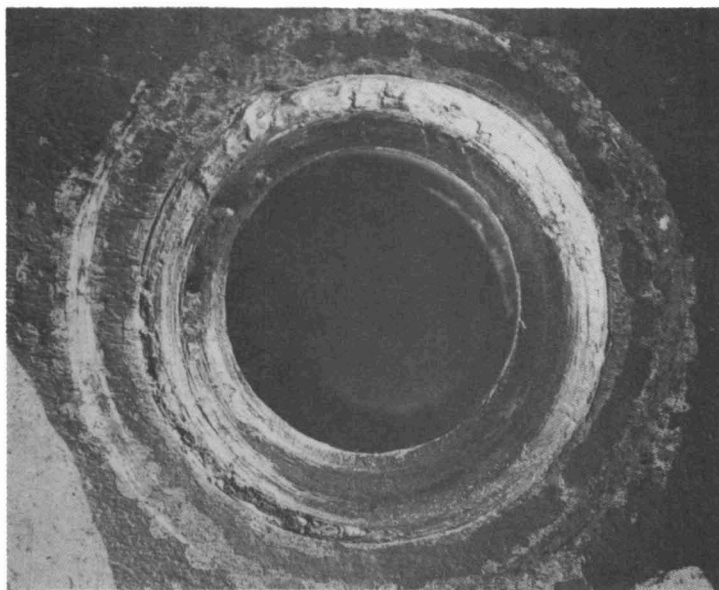
FIG. 9(a)   Galling of Plate Under Turned Element - Joint OH1-2
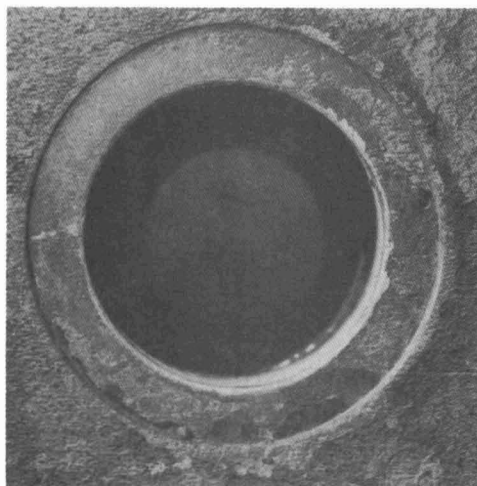
FIG. 9(b)   Depression Under Bolt Head - Joint OH1-2 (1/16-in. Clearance)
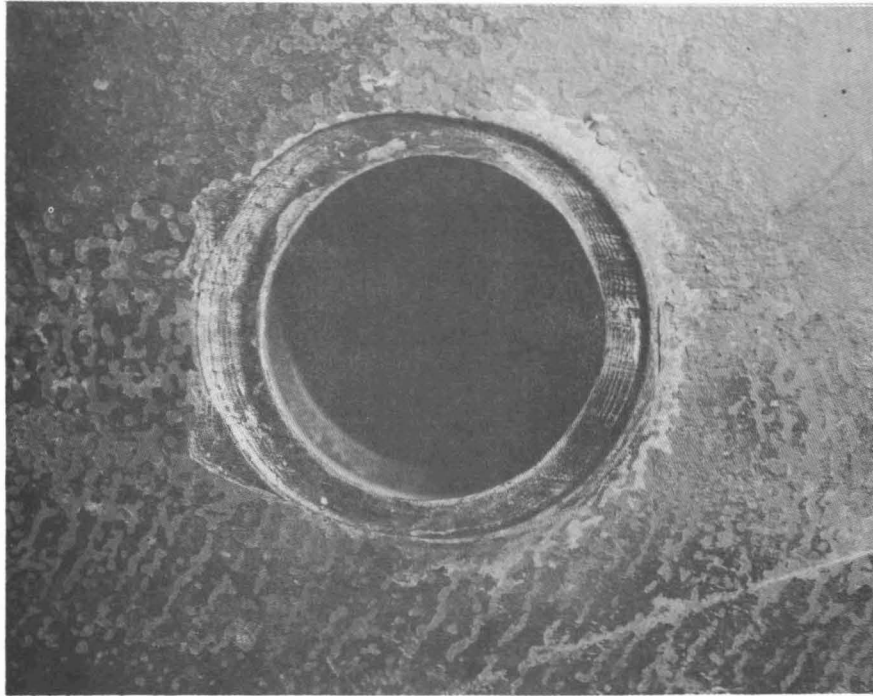
FIG. 10(a)   Depression Under Bolt Head - Joint OH2-1
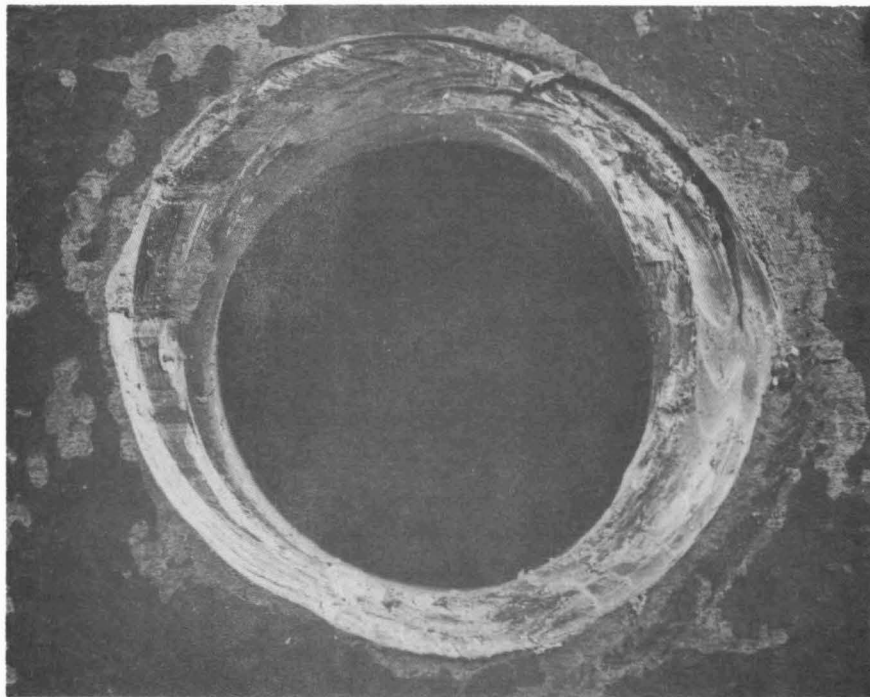
FIG. 10(b)   Severe Galling of Plate Under Turned Element - Joint OH2-1
(1/4-in. Clearance, No Washer)

FIG. 11   Plate Area Under Turned Element Where a Washer Was Used - Joint OH3-2
(1/4-in. Clearance)
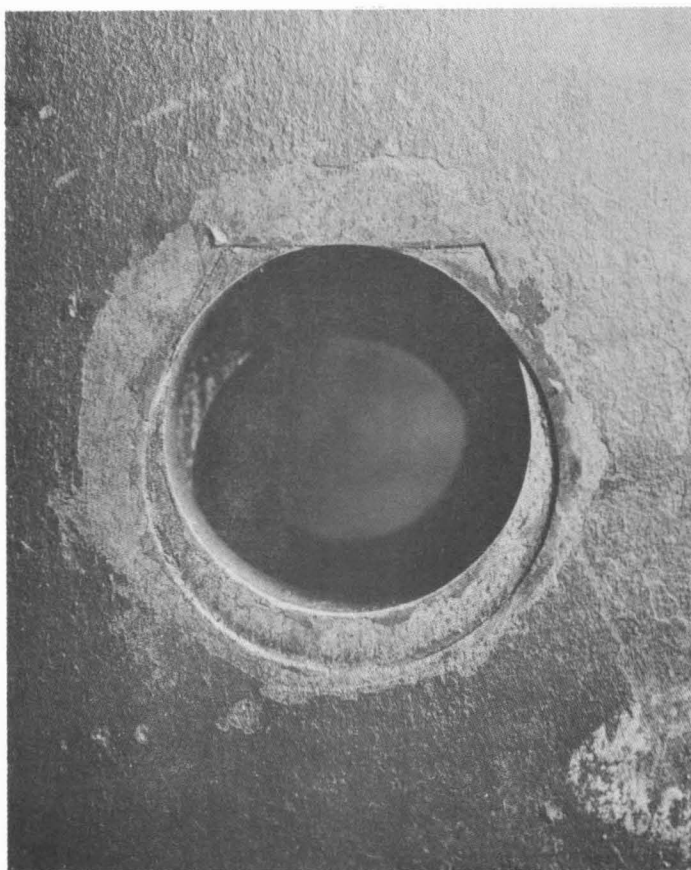
FIG. 12   Depression Under Bolt Head - Joint OH4-2
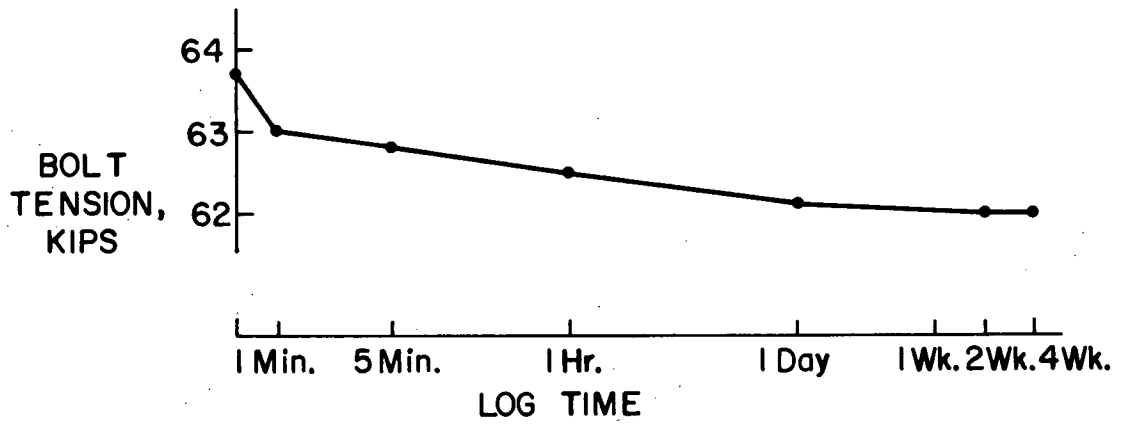
FIG. 13   Time-Tension Relationship of Bolt XB-29 in Joint OH1-2
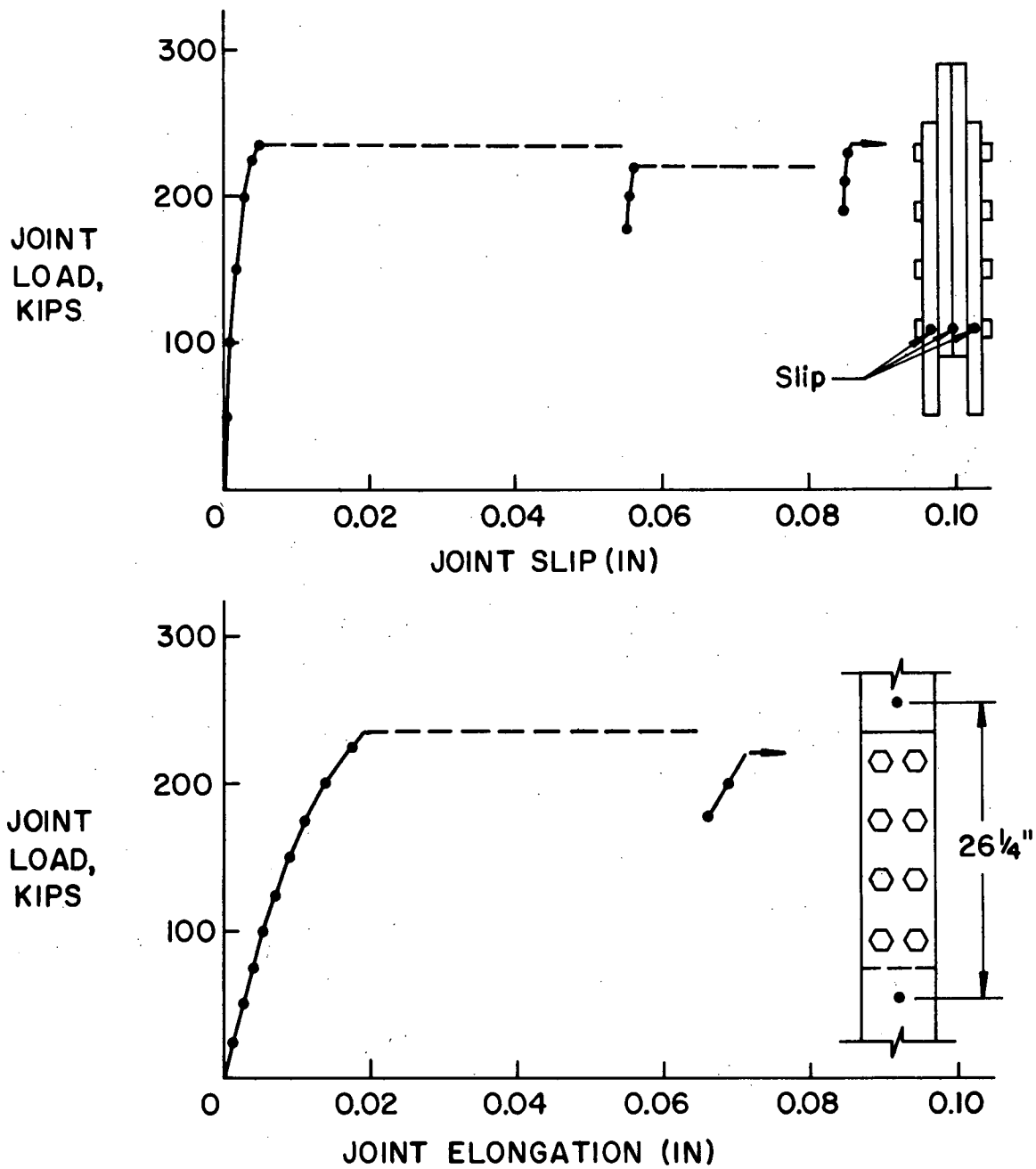
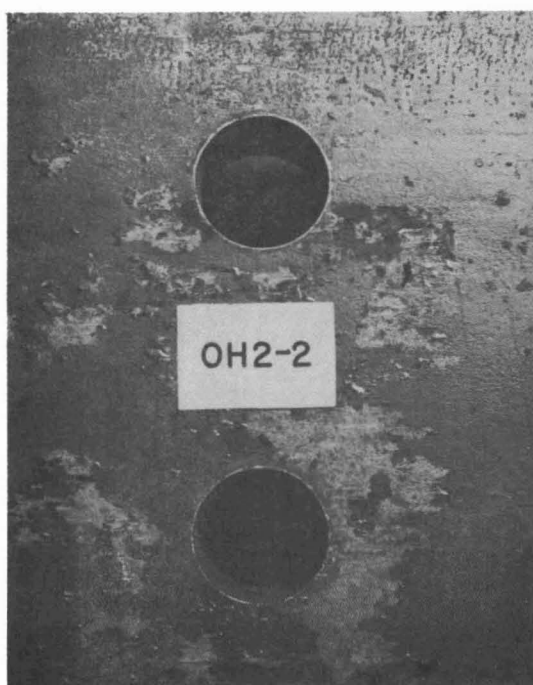FIG. 14   Joint Slip and Elongation of Joint OH4-3
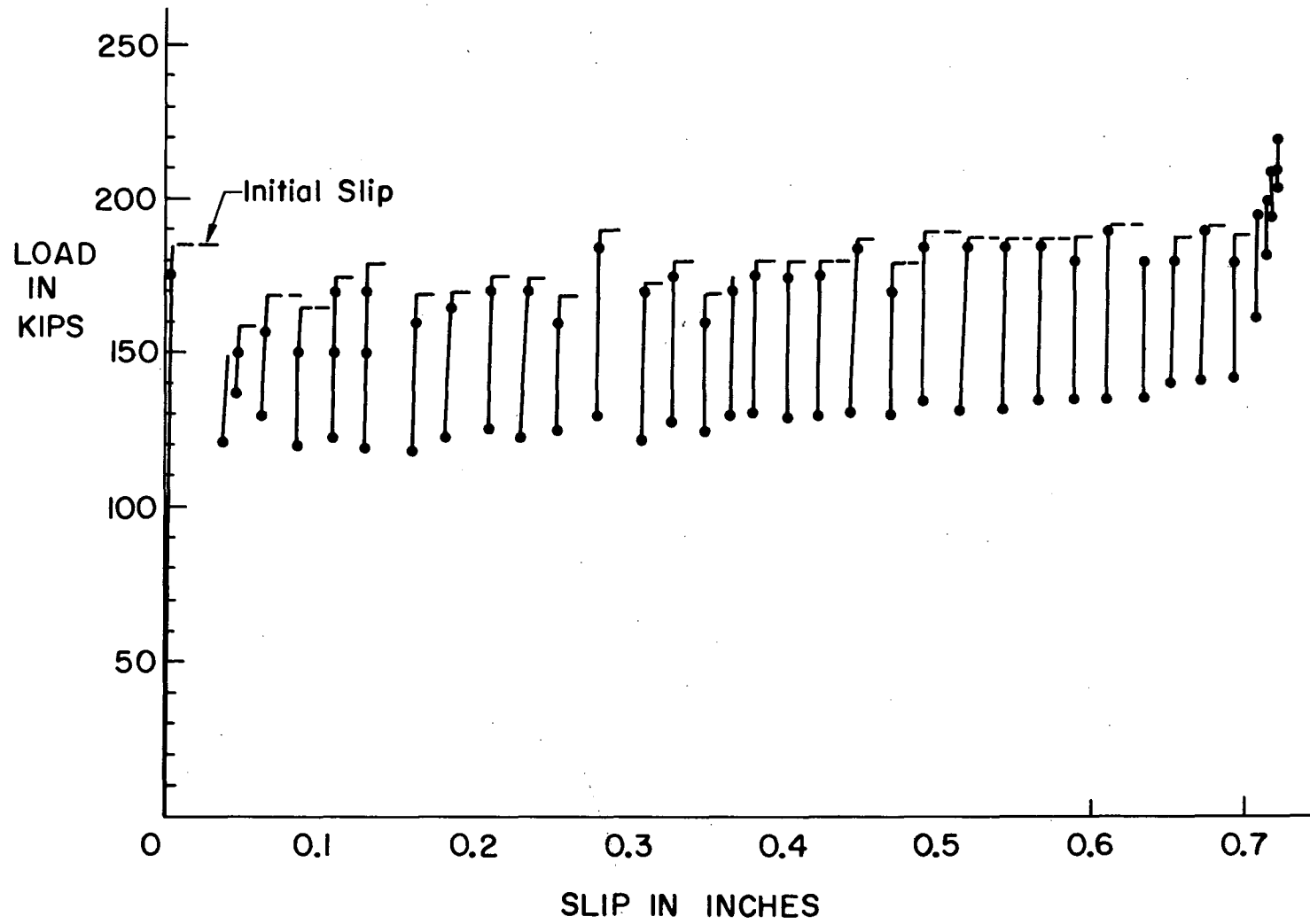
FIG. 15   Load-Slip Diagram of Joint SH1-1

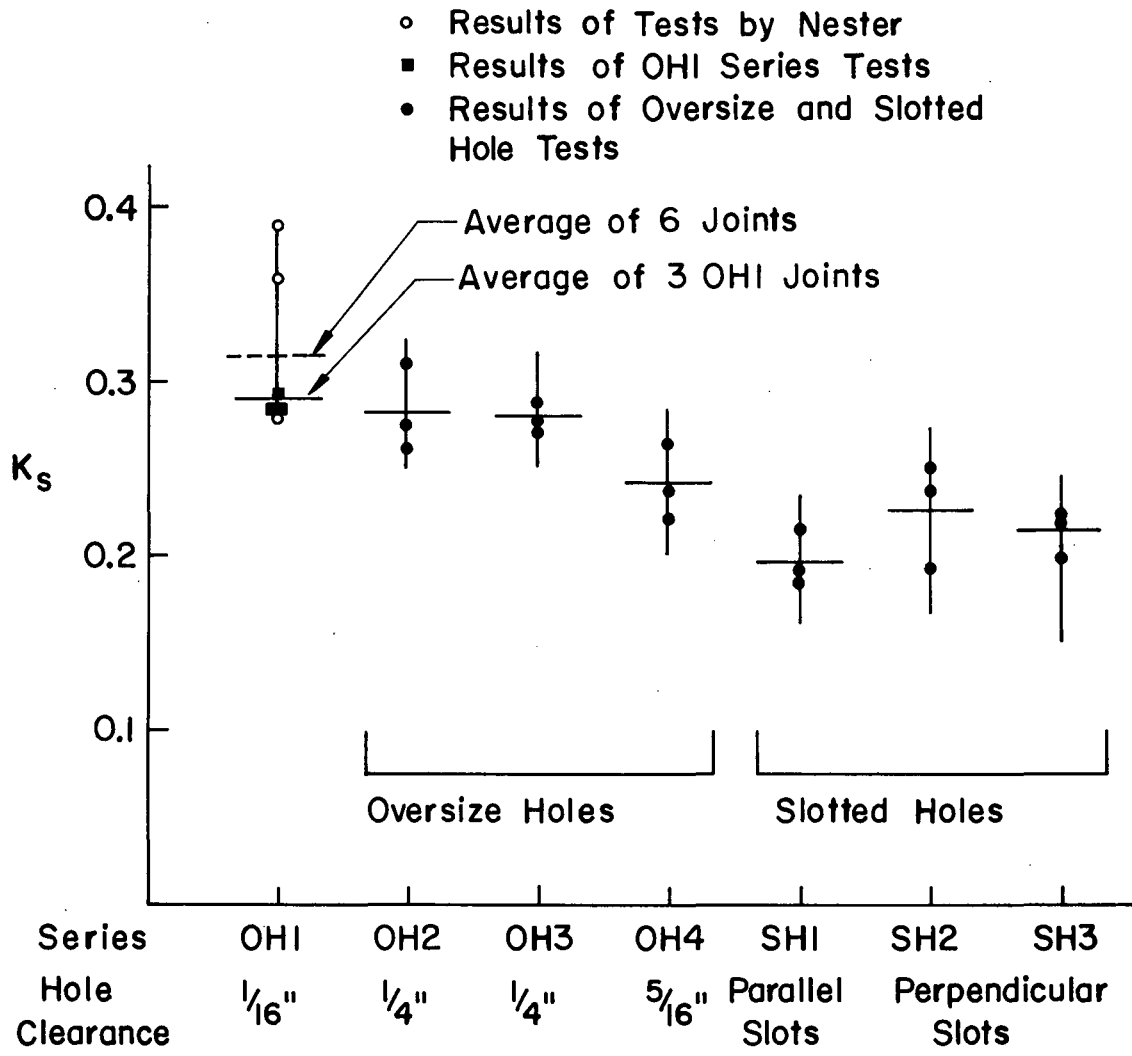FIG. 16   Faying Surface Damage of OH2 Joint (1/4-in. Clearance)

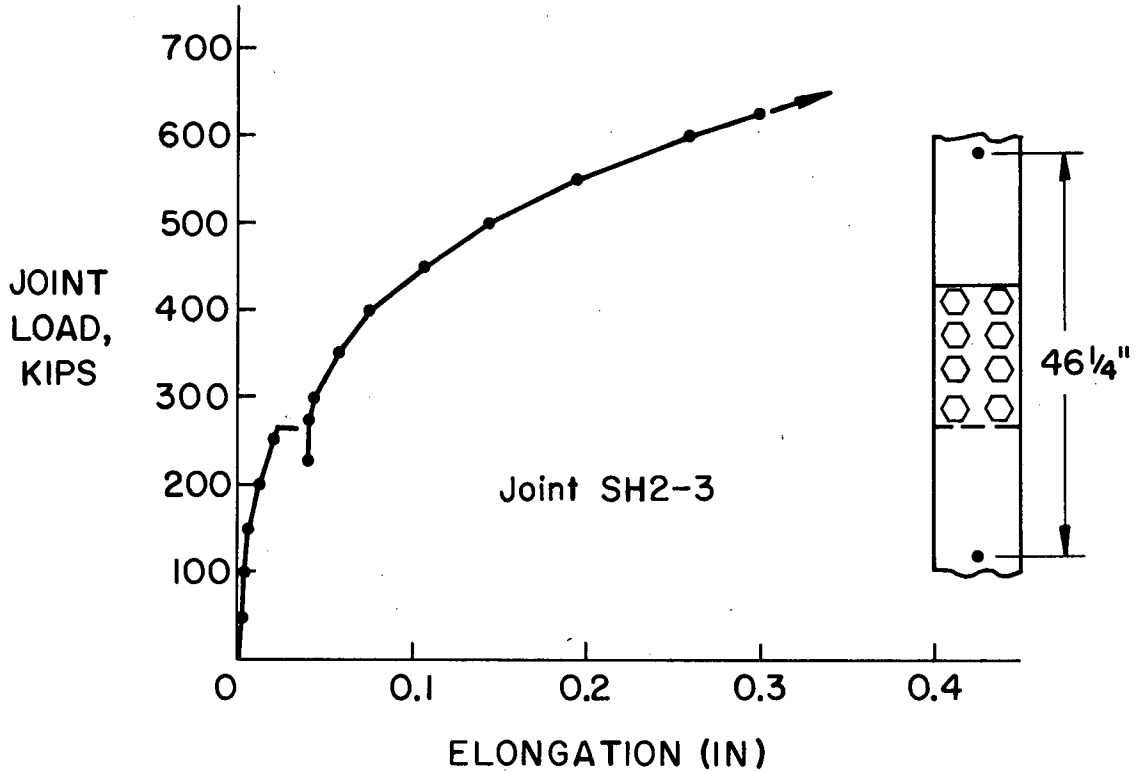FIG. 17   Comparison of Average Slip Coefficients
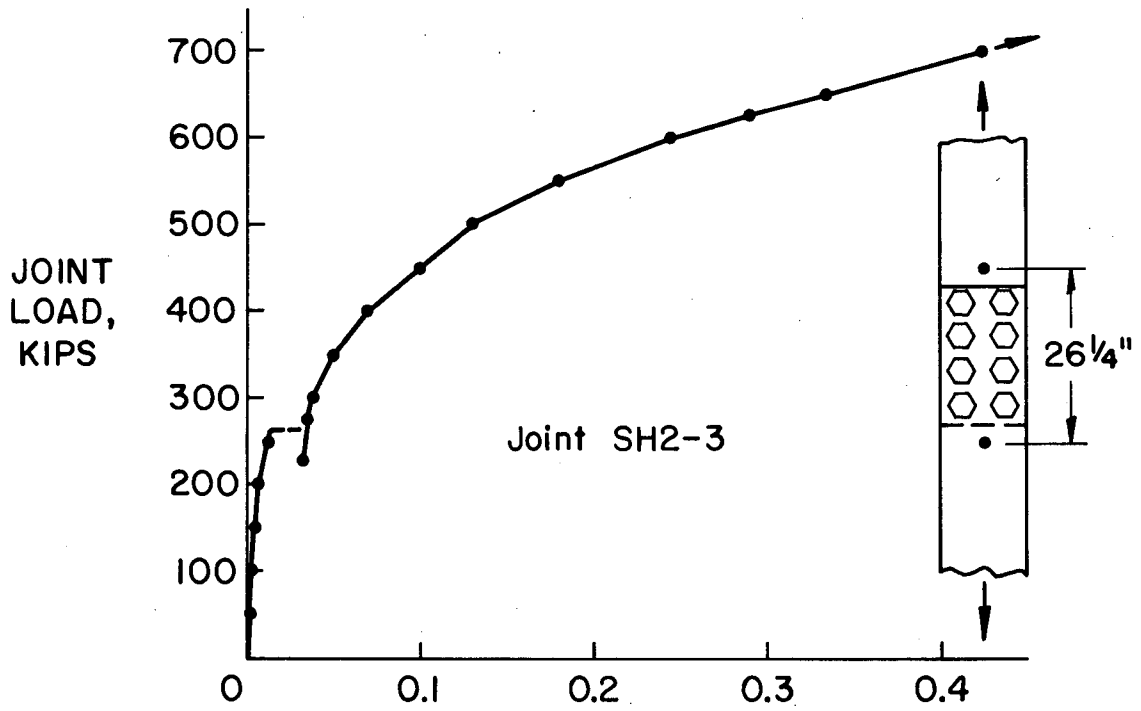
FIG. 18   Load-Joint Elongation and Load-Specimen Elongation of Joint SH2-3

FIG. 19   Deformation of Slotted Holes
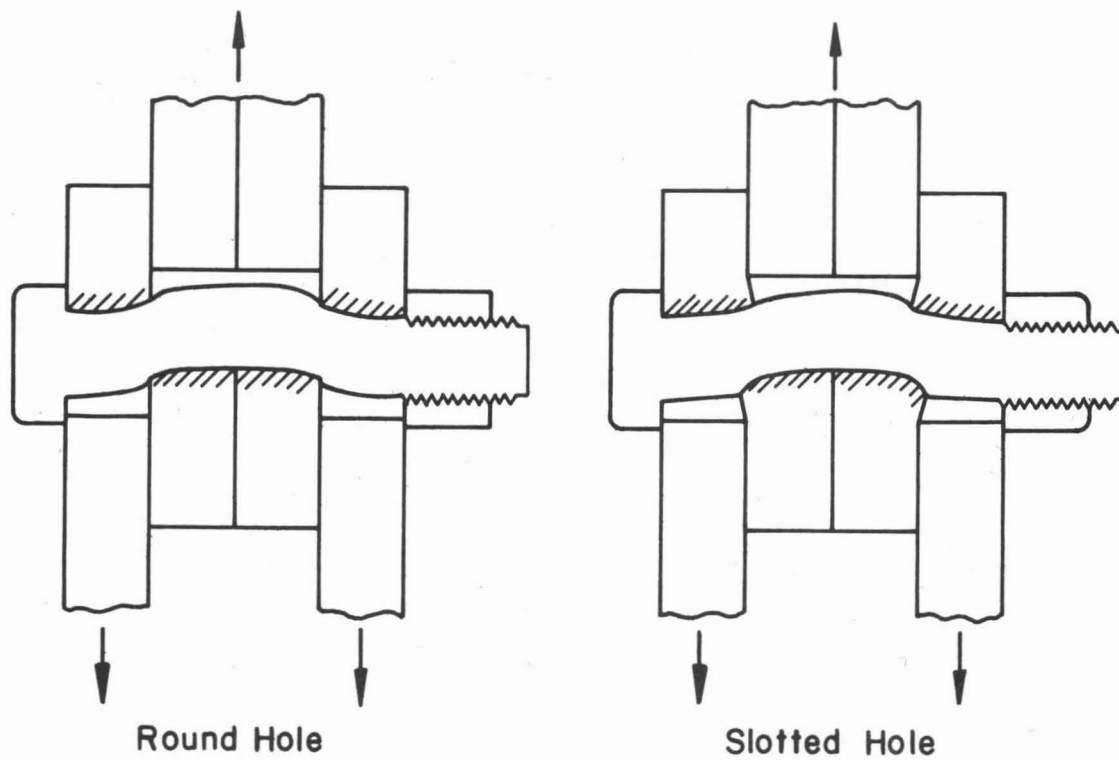
Round Hole   Slotted Hole

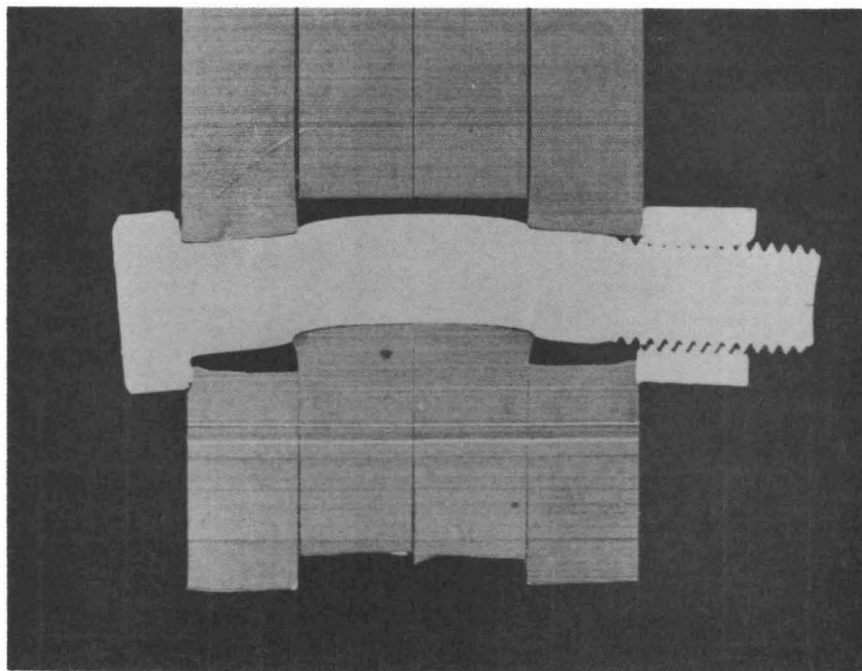FIG. 20   Comparison of Bolt and Plate Deformations

FIG. 21   Deformed Plates and Bolt in Sawed Section of Joint SH3-2
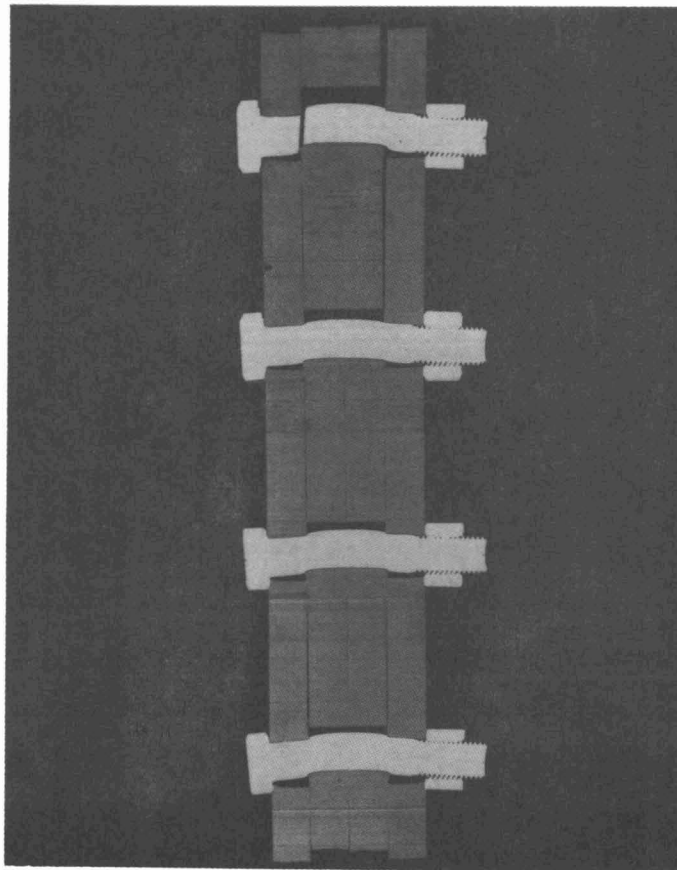
FIG. 22   Sawed Section of Joint SH3-2

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