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SYNOPSIS

Tests of structural joints of A440 steel, connected with A325 high-strength bolts installed by the turn-of-nut method, were conducted to determine their slip resistance and ultimate strength. The purpose of the program was to establish an approximate shear stress value for bearing-type connections and to determine the influence of joint length on the ultimate strength of higher strength steel connections. Eleven of the joints tested had two lines of fasteners, ranging from 4 to 16 fasteners in line. Other joints had four and six lines of fasteners.

The ultimate strength of the joints, with the theoretically predicted values based on the non-linear behavior of the component parts, shows good correlation between the theoretical analysis and the test results. These studies together with the earlier work with structural grade steel have aided in the development of a rational basis for design.

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1. INTRODUCTION

Applications of high-strength bolts have been expanded considerably since the Research Council on Riveted and Bolted Structural Joints adopted its specification for bolted joints in 1960[1]. One of the most important provisions of this specification was the change in the allowable shear stress for bearing-type connections. This allows the substitution of two bolts for three rivets. The experimental and theoretical research studies on which these design rules were based considered only connections fabricated with ASTM A7 steel.

The increased use in recent years of high strength steel for construction purposes has created a need for research to investigate the behavior of these steels when used in connections fabricated with A325 high-strength bolts. With the higher yield stress level the overall behavior of connections made with ASTM A440 steel may differ from the behavior of connections made with ASTM A7 steel.

A great deal of information has been obtained on the behavior of connections using A7 steel in previous research programs[2,3]. With this information as background material, it was the purpose of the present work to study:

1. The basic behavior of ASTM A440 steel connected with ASTM A325 bolts;

2. The appropriate shear stress to be used in compact joints;

3. The possible reduction of shear strength associated with long connections of this material;

4. The effect of internal lateral forces caused by plate necking near the ultimate strength of the joint; and

5. Any effect on the behavior of the joint caused by the presence or absence of washers.

In addition to the large scale tests, the behavior of the individual elements of a joint was established in this study. The properties of the plate material and the bolts were determined from plate coupon tests, plate calibration tests, direct-tension and torqued tension tests of the bolt, and double shear tests of the bolts. A theoretical analysis was made to predict the ultimate strengths of the connections tested.

Very little previous research has been carried out on large bolted bearing-type connections using high-strength steels. In 1957 a demonstration test of a compact A242 high-strength steel specimen connected by nine A325 and nine A354BD bolts was performed at Northwestern University[4]. The joint was designed in such a way that plate failure occurred. Other tests of small specimens were conducted at the same University in connection with a fatigue test program[5].

2. DESCRIPTION OF TEST SPECIMENS

1. Pilot Tests

Six compact joints were tested to determine the appropriate shear stress for such joints. Each specimen was one half of a double shear butt joint as shown in Table 1. These tests were designed to determine the ultimate strength of the fasteners in shear that would develop the tensile capacity of the net section of the main material. Coupon tests had established the ultimate tensile strength as approximately 75 ksi, the shear strength of a single bolt was found to be approximately 85 ksi, and therefore the required shear area of fasteners would seem to be only slightly less than the net plate area. The pilot tests also were conducted to determine if variations in the net plate area had any influence on the shear strength of bolts in a joint. In addition, a study was made of the effect the presence or absence of washers had on the behavior of these joints.

In previous investigations of riveted and bolted joints[2,3,6] the concept of tension-shear ratio (T:S) at "balanced design" has figured prominently in determining allowable stresses. As discussed in Ref. 7, it is likely that this concept is not applicable in general to materials other than A7 steel used in relatively short joints. Nonetheless, for reference purposes the T:S ratios are shown in the tables. As indicated in Table 1 the tension-shear ratio used in these tests ranged from 1:1.10 to 1:0.90.

The difference in behavior of joints fabricated with regular head bolts with the 1960 ASA[8] standard thread and of joints fabricated with heavy head bolts with the shorter thread length was also studied. In all joints the shearing planes passed through the shank portion of the bolts.

The first four joints, E41a, E41b, E41c, and E41e consisted of two lines of four 7/8-inch diameter A325 regular head bolts. The shear area to tensile area ratio for these specimens was varied from 1 to 0.90 to 1 to 1.10 by varying the plate widths in the joints. Each regular head bolt in these four joints was provided with one washer under the head and one under the nut.

Joints E41f and E41g were fabricated in the same manner and from the same plate material used for the other four joints. Heavy head bolts were installed in these two joints instead of regular head bolts. The number of washers also differed from the number used in the first four specimens. Joint E41f was provided with a washer under the nut only and joint E41g had no washers under head or nut.

The test specimens for the pilot series were proportioned so that at ultimate load the shear strength of the fasteners was nearly equal to the tensile capacity of the net section. Hence,

$$A_n \sigma_n \cong A_s \tau_t \qquad (1)$$

where A_n = net tensile area

A_s = bolt shear area

σ_n = stress on the net section (ultimate)

τ_t = shear strength of the bolt (ultimate)

When the ultimate loads are "balanced"

$$\frac{\sigma_n}{\tau_t} = \frac{A_s}{A_n} = \frac{T}{S} \quad \text{(tension-shear ratio)} \qquad (2)$$

For two lines of four 7/8-inch bolts with 15/16-inch drilled holes, a main plate thickness of 2 inches, and two shear planes, the plate width changed from 6.20 to 7.16 inches as the ratio T/S was varied from 0.90 to 1.10.

2. Long Joints

Each of the long joints had two lines of 7/8-inch A325 heavy head bolts with a pitch of 3.5 inches. Each bolt had a washer under the nut only. The number of bolts in line varied from joint to joint, from four to sixteen.

Based on results obtained from the pilot tests, these subsequent test specimens were proportioned by providing a net plate area equal to the shear area of the bolts. Since the shear area in a joint is dependent upon the number of bolts, the shear area varied for the long joints. In order to maintain equality between shear and tension areas, it was necessary to vary the net area of the joint. This was accomplished by varying the width and the thickness of the plate material. As the number of 7/8-inch bolts in line varied from 4 to 10, the plate width varied from 6.68 to 13.88 inches with a 4-inch grip. In the case of the joints having 13 to 16 bolts in line, the plate width varied from 9.70 to 11.50 inches with an 8-inch grip. Table 2 outlines the nominal dimensions for these specimens.

3. Wide Joints

The three specimens in this group to study the effect of joint width were designed and fabricated as described previously. Heavy head 7/8-inch A325 bolts were used with a washer under the nut only.

Joint E46 was the same as joint E41 in the "long joint" series except that the number of lines of bolts and the plate width were three times as great.

Joint E74 was identical to joint E71 except that it had twice the number of lines of bolts and was twice as wide. Because of premature failure of the main plate outside the joint in this specimen, another joint was fabricated and tested. This duplicate of joint E74 was called E741. Table 3 outlines the nominal dimensions of the specimens E46, E74 and E741.

3. MATERIAL PROPERTIES

1. Plates

The plate for all joints in this series of tests was ASTM A440 structural steel cut from Universal Mill strips 8 or

26 inches wide by 1 inch thick and approximately 36 ft. long. Two different heats of steel were used, one for the pilot investigation and one for the other tests.

At least two plate coupons were cut from the material of each joint tested. These coupons were 1 inch thick and were milled to 1.5 inches in width. Table 4 gives a complete summary of all coupon properties and lists mean values and corresponding standard deviations.

A typical stress-strain diagram is shown in Fig. 1. The initial portion as determined from an autographic strain recorder is shown expanded, and the complete curve as measured with caliper is also shown.

In all tests both the yield stress and the static yield stress levels were recorded. The yield stress level is reported for a strain offset of 0.2%. The static yield stress level for each coupon was taken as the mean of the minimum values as shown in Fig. 1. Standard deviations are also shown in Table 4, and in order to determine whether or not there was a significant difference between the means for the yield stress levels and the ultimate strengths of the different heats, the "t" test for a five percent level of significance was applied[9]. There were no significant differences found in the yield stress levels or ultimate strengths of the two heats of material. This also is confirmed by a visual inspection of the means and standard deviations listed in Table 4. The plate material was purposely ordered near the minimum requirements specified by ASTM for A440 steel.

In order to establish the behavior of the plate elements, special plate calibration tests were conducted by testing a plate of the same material used in the large joints. The plate had a width equal to the gage distance, a thickness of 1 inch, and two holes drilled 3.5 inches on center as shown in the inset in Fig. 2. The tension-elongation relationship was recorded for the material with the distance between the hole-centers as gage length, which was equal to the pitch length in the large joints. The load-elongation curves for these tests are shown in Fig. 2. These curves are essential to the theoretical prediction of the ultimate strength of the bolted joints.

2. Bolts

The bolts were 7/8-inch ASTM A325 bolts. The length of the bolt under the head varied from 5.25 to 9.5 inches. All bolts were the heavy head type with short thread length except for the bolts in four of the pilot tests in which regular head bolts were used. The thread lengths are listed in Table 5.

Each bolt lot was calibrated according to the procedures described in Ref. 10 to determine its direct tension and torqued tension behavior. A brief summary for each lot is given in Table 5.

Bolt shear tests were conducted to establish the relationship between the shearing load carried by a single bolt and its deformation. Two different types of tests were conducted as indicated by the sketches in Fig. 3. In one type the bolts were subjected to double shear by plates loaded in tension, and in the other test the bolts were subjected to double shear by applying a compression load to the plates. The plates were fabricated from the same material and had the same grip length as the corresponding assembled joints. Three bolts were tested from each lot in each type of test. The results of the tests of the 8B lot bolts are given in Fig. 3.

The shear strength of single bolts tested in plates loaded in tension was approximately 10% less than the shear strength from the compression test. When bolts are loaded by plates in tension, the bearing condition near the shear planes causes a prying action and results in an additional tensile component which reduces the bolt shear strength. The catenary action resulting from the deformations may also contribute to the tensile component. In addition to reducing the bolt shear strength some reduction in the deformation capacity is also apparent. When bolts are loaded by plates in compression it simulates the condition of bolts in the interior of joints as the prying action is minimized.

4. FABRICATION OF TEST JOINTS

1. Fabrication

All shop work necessary for the fabrication of the test joints was done by a local fabricator. The shop procedure was the same for all specimens. Plates were first cut by torch and then machined to the final dimensions. Loose mill scale was removed by hand brushing with a wire brush. Oil and grease were wiped from the plates in order to establish a faying surface condition which would prevail in field assembly.

For the wider joints it was necessary to reduce slightly the width at the ends in order to grip the specimens in the testing machine. This was done with a torch in the cases of Joint E46 and E74. Special attention to this transition was given with Joint E741, where all edges were ground to a smooth transition after the rough burning.

The plates for each joint were assembled into a general joint configuration and then clamped together. The four corner holes were subdrilled and reamed for alignment. Pins machined to fit the reamed holes were inserted to hold the joint in alignment while the remainder of the holes were drilled through all plies of the joint. All holes were drilled 15/16-inch in diameter to allow 1/16-inch clearance for the 7/8-inch bolts.

2. Assembly

The bolting-up operation was carried out at the Fritz Engineering Laboratory by a field erection crew of the fabricator. This arrangement made it possible to gather information concerning the bolt tension.

With a few exceptions, the bolts were snugged with the impact wrench and then given a prescribed rotation depending upon the bolt diameter and grip length[1]. All bolts in joint E41b and four bolts in joint E741 were installed with a hand torque wrench and tightened to the corresponding average bolt elongation. The diameter of all bolts used was 7/8-inch and the grip was 4 inches for all the joints except two in the long series (E131 and E161).

Complete records of bolt elongations were kept for each bolt in every joint of the test series. The initial length was measured some time before the bolting-up operation. The final length was measured after installation.

5. INSTRUMENTATION

The instrumentation for all of the test specimens was essentially the same except for joints having more than two lines of bolts. Figure 4 shows joint E74 in the testing machine with instrumentation attached. Included were SR4 strain gages, a mechanical extensometer and dial gages. Following is a short description of the purpose of these gages and measuring devices.

SR4 electrical resistance strain gages were generally attached only to the edges of the main and lap plates. These gages were used to detect eccentricity due to improper gripping and to pick up the onset of yielding of the gross section. Additional gages were attached to the faces and dead end of the lap plate of wide joints E46 and E74 in order to study the effect of any internal lateral forces caused by plate necking near ultimate load.

For joint E741, four bolts were prepared, each having two SR4 strain gages attached to the bolt shank near the bolt head to detect changes in the bolt tension during testing of the joints. During installation of these bolts strain readings were taken and related to calibration tests conducted on the same type of bolts so that the initial bolt tension was known.

The elongation of each pitch of the joint was measured along the edges of the plates with a mechanical extensometer. These measurements were used to check the accuracy of the theoretical solution for the load partition and ultimate strength of the bolted joints.

During the tests of joints E46 and E74 the mechanical extensometer was used to record the transverse and longitudinal plate deformations between bolts of one of the lap plates. The transverse measurements gave some indication of the forces due to plate necking. The longitudinal measurements were compared with the pitch measurements made on the edges of the plates.

Dial gages (0.001 in.) were used to measure the over-all elongation of the joint and provide control during the testing operation. More sensitive gages (0.0001 in.) were used to measure the slip between the lap and main plates as well as the relative displacement between plies of material making up the lap and main plates of joints E131 and E161.

6. TEST PROCEDURE

The joints were loaded in static tension by a 5,000,000-lb. hydraulic testing machine using wedge grips. The specimen was gripped, and testing proceeded in equal load increments until major slip occurred. Very close observation of the dial gages as the expected slip load was approached, made it possible to record the displacement at the instant prior to the occurrence of slip. After slip, load was again applied in equal increments until major yielding of the plate material occurred. In the inelastic region, after applying an increment of load the specimen was allowed to stabilize at a constant strain value. The amount of additional strain which took place during stabilization of the load was small as attested by dial gage readings. This procedure was followed until failure of the joint occurred. The load-deformation relationship shown in Fig. 5 was typical for all specimens. In the longer joints failure occurred when an end bolt sheared. All joints with four bolts in line (except E41a) showed a sudden and complete shearing of all bolts.

7. TEST RESULTS

1. Pilot Tests

A complete summary of the results for the pilot test series is given in Table 1. Joint E41a failed by a tearing of the main plates whereas all other specimens experienced simultaneous failure of all bolts.

All joints experienced a sudden major slip as indicated for a typical joint in Fig. 5. This slip occurred at a nominal bolt shear stress which varied from 27.0 to 29.3 ksi. except for joint E41b. Table 1 shows all test data. In joint E41b first major slip occurred at a nominal bolt shear stress of 20.6 ksi. This premature slip may have occurred because of warping of the joint during bolting-up. The joint was bolted-up by hand while lying in a horizontal position. This resulted in a curvature out of the loading plane and evidently the eccentric loading condition caused an earlier slip. All joints had tight mill scale faying surfaces.

For the five joints which failed by simultaneous shearing of all bolts the nominal bolt shear stress at failure varied from 75.6 to 81.3 ksi. Joints E41b, E41c and E41e were fabricated from the same plate material and connected by the same lot of bolts.

2. Long Joints

A complete summary of the results for all the long joints is given in Table 2. Only joint E41 failed because of simultaneous shearing of all the bolts. In the other joints one or more end fasteners "unbuttoned" and the joint remained intact. The load at which the first bolt sheared has been considered the failure load even though complete rupture had not occurred. As a check, in the case of joint E101, load was re-applied until a second bolt unbuttoned -- at a slightly lower load. The sequential failure of the fasteners was similar to that reported in Ref. 3 for A7 steel joints.

Major slip occurred at nominal bolt shear stresses which varied from 23.8 to 26.7 ksi. as shown in Table 2.

All of these joints failed by a shearing of one or more bolts. The average bolt shear stress at failure varied from 75.7 to 66.2 ksi. as the joint length varied from 10.5 to 52.5-inches in length (4 to 16 fasteners in line).

A visual record of deformation of bolts along the length of joint E71 is given in Fig. 6. The high stress in the plates at the ends of the joint is revealed by the larger elongation at the end holes. The prying action at the lap plate end is revealed by the separation of the plates. Fig. 7 shows joint E101 after unbuttoning of both top bolts. The offset of the bolt shank remaining in the joint can be seen. The load-deformation relationship for this joint was given in Fig. 5.

3. Wide Joints

The results of the three tests on the wider joints are summarized in Table 3. All joints experienced a sudden major slip.

Joint E46, a compact wide joint with 24 bolts in its pattern experienced first major slip at a nominal bolt shear stress of 27.7 ksi. No other minor slips were observed thereafter. The ultimate load was 2180 kips.

First major slip occurred in joint E74 at a nominal bolt shear stress of 27.1 ksi. Several minor slips were recorded thereafter but produced no significant effects. Failure occurred at a load of 2410 kips when one bolt unbuttoned.

Joint E741 experienced first major slip at a nominal bolt shear stress of 20.2 ksi. Several minor slips were noticed thereafter until the joint came into full bearing. Failure occurred when one of the corner bolts of the lap plate end unbuttoned at a load of 2250 kips.

8. ANALYSIS OF RESULTS

1. Ultimate Strength

As expected all joints with equal tension and shearing areas failed by shearing of one or more bolts. In joints with four rows of bolts simultaneous shearing of all the bolts occurred. In the longer joints one or more of the bolts in the lap plate end unbuttoned due to their larger deformations and the combined stress state.

The results of the tests are shown in Fig. 8 as solid dots where the ultimate strength of the joints are represented by an "unbuttoning factor". The length of each joint is shown both as actual length and in terms of the number of pitches (3.5 in.).

Because bolts of several lots and strengths were used, it is convenient to represent the average shearing stress at failure in non-dimensional form. This non-dimensional quantity is called the unbuttoning factor (U) and is computed by dividing the average ultimate shear stress of the joint (τ_{av}) as given in Tables 1, 2 and 3 by the tension shear strength of a single bolt (τ_t) as given in Table 5. Thus,

$$U = \frac{\tau_{av}}{\tau_t} \qquad (3)$$

The unbuttoning factor U describes, in effect, the extent to which the bolts in a joint are able to redistribute forces. If it was equal to unity then all fasteners would carry an equal share of the load at ultimate -- just like a single fastener.

In Fig. 8, a decrease in the unbuttoning factor can be seen as between the compact and the longer joints. However, this decrease is at a decreasing rate and appears to approach an asymptotic value of approximately 0.80. For joint lengths greater than 20 inches the average shear stress of the bolts in the joint at failure was about 80% of the shear strength of a single fastener.

The test results are compared with the theoretical solution in Fig. 8, the latter being shown by a dashed line. The ultimate strength of the test joints was computed with the equilibrium and compatibility conditions formulated in Ref. 11. It is a method which is based on the load-deformation relationship of the plate material loaded in tension (Fig. 2) and that of the high strength bolts loaded in shear (Fig. 3). A similar method was used in Ref. 12 for aluminum alloy riveted joints. Since the behavior of the bolt in shear is somewhat different depending on whether the shear jig is loaded in compression or in tension, the theoretical result will depend upon which shear curve is used.

The theoretical curve in Fig. 8 is based on the behavior of a bolt loaded in a tension shear jig. It is seen that the actual strength is somewhat greater than the predicted value. This is to be expected as not all bolts are subjected to the prying action experienced by the end rows. This same information is given in Table 6 in comparison with the test results; along with these, are shown the results obtained using the shear deformation relationship given by the compression test of a single fastener ("method 1"). As expected, the latter predicts a higher strength. The results from a third method are also shown in Table 6: The bolts in the end two rows at each end of the joint were assumed to be represented by tension loading because of the prying action, and for the remaining bolts the compression shear-deformation relationship was used. Although this method gives the most precise agreement (within one percent) the refinement may not justify the added work.

Figure 9 shows the comparison of these joints of A440 steel with those of A7 steel. The average shear stress has been taken as the product of the unbuttoning factor and the minimum tension shear strength of a single bolt. The "compression" and "tension" shear strengths of single bolts are also shown in the figure. For short joints the higher strength steel results were about the same as A7, the test average being shown by the solid line; but in the long joints the performance of A325 bolts was better in the A440 steel.

A part of the reason for the improved performance of the A325 bolt when used with higher strength steels is illustrated in Fig. 10. Here the computed bolt shear stress in each row at two different stages are shown for joints of equal length and the same number of A325 fasteners.* The upper set (joint E101) is for A440 steel, the lower set (D101) is for A7 steel, and the geometry of the joint is shown between the two graphs.

The figure indicates that the higher yield strength steel effects a better distribution of the bolt forces, the stresses being more uniform in joint E101 than in the case of D101. At failure, in D101 (A7 steel) the stresses in the bolts near the middle of the joint were less than half those of the end bolts. The higher yield stress of the A440 steel in E101 allowed a better redistribution because inelastic deformations occurred in all bolts while the plate material

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* The computations are based on the methods described in Ref. 11.

was still elastic and relatively rigid. In the lower yield stress A7 steel, inelastic deformations occurred first in the plate (and nearly simultaneously in the end fasteners), and this caused increased deformation in the end fasteners. As a result the end bolts continued to pick up load at a faster rate and did not allow redistribution to occur as well as in the higher yield strength steel. As illustrated in Fig. 10 the interior bolts in the mild steel joint showed little change in load-carrying ability from the onset of major yielding until an end bolt failed.

These results suggest that allowable stresses to be used for long A440 joints might well be higher than that permitted for similar A7 steel joints. A more detailed discussion concerning the design of bolted joints can be found in Ref. 7.

2. Effect of Joint Width

The effect of internal lateral forces caused by plate necking near the ultimate tensile strength of a wide joint was investigated with tests of three joints (E46, E74 and E741 as shown in Table 3).

Joint E46 had a width three times as great as joint E41. By comparing the results in Table 3 with those in Table 2, the failure load of 2180 kips for E46 is seen to be exactly three times the ultimate load of E41. The joint width had no effect on the ultimate strength in this case. The test point is plotted in Figs. 8 and 9 as an open circle.

Joint E74 (seven bolts in a line with four lines) unbuttoned at a load of 2410 kips. This was slightly more than twice the ultimate strength of joint E71 with seven bolts in line but with only two lines of fasteners. Again joint width had no effect on the ultimate strength. After slip load occurred, but prior to bolt fracture, joint E74 failed prematurely in the region near the grips. The above result was obtained after the gripping area was repaired. In Fig. 8 the test point for E74 can be seen as the topmost of the three shown at six pitches.

Joint E741 was a duplicate of joint E74. This joint was fabricated and tested because of the failure in the grip region experienced in joint E74. Joint E741 failed when a corner bolt unbuttoned at a load of 2250 kips. This load was about 5% less than twice the ultimate strength of joint E71, and the corresponding test point is shown in Fig. 8 as the lowest of the open circles at six pitches.

Strain gages, placed transverse to the line of load on the "dead" end of the lap plates of joints E46 and E74, indicated compressive strains between bolts. This constituted a direct indication of the presence of lateral forces because of the suspected Poisson's effect in the wide joints. The corresponding bolt shear force acting perpendicular to the joint load was estimated to be approximately 4 to 12 ksi. However, once major yielding occurred in the main plate and large shear deformation developed in the bolts, the transverse strains were reduced until the transverse bolt shear stress was estimated to be 1 to 5 ksi.

With these results it is thus concluded that the effect of joint width is not significant in butt joints of A440 steel plate fastened with A325 bolts. Plate necking was found to contribute to the premature corner bolt failures in joints of A7 steel(2).

3. Effect of Variations in Plate Area

The pilot test series for the A440 steel joints allowed an evaluation of the performance of the bolts when the tensile area was varied. As the plate area at the net section was increased from 95 to 110% of the bolt shear area, the bolt shear stress increased from 78.4 to 81.3 ksi. as indicated in Table 1. This increase is to be expected as the larger plate area has a greater "stiffness" and allows a better redistribution.

The results of tests of A7 steel joints which had large variations in the plate area were analyzed and discussed in Ref. 7. The same type behavior was found for both A7 and A440 steel when the plate area was varied.

When the net plate area is decreased relative to the bolt shear area the joints invariably fail by tearing of the plate such as was the case for joint E41a (see Table 1). As a result, there is no way to determine the shear strength of the fasteners. For the compact A440 steel joints this occurred when the plate area was 90% of the bolt shear area. This same phenomenon was observed in compact A7 steel joints at approximately 95% of the bolt shear area[2].

4. Joint Slip

The factor which determines the load at joint slip is called the "nominal coefficient of friction" or "slip coefficient" (K_s). This slip coefficient necessarily depends on the condition of the faying surfaces and the clamping forces induced by the bolts. On the basis of a visual inspection the rolled mill-scale surface of A440 plate material used in the test joints was quite hard and smooth. The bolts were tightened according to the turn-of-nut method[1] and resulted in bolt clamping forces which showed no marked variations from the average bolt tension.

Bolt elongations were measured during fabrication. The histograms of the bolt tension distribution were similar to those reported in Ref. 2. The average elongations and their corresponding bolt tension are given in Tables 1 to 3. The mean elongation ranges from 0.033 to 0.0463 inches for half of a turn and is about 0.0556 inches for three quarters of a turn. The corresponding bolt tension is approximately 1.3 times the proof load of 7/8-inch A325 bolts in either case. The nominal slip coefficients obtained for each joint are recorded in Tables 1, 2, and 3. The average slip coefficient computed for these tests was $K_s = 0.32$. The slip coefficients were determined from the relationships given in Ref. 2.

Figure 11 is a bar graph which illustrates the slip resistance of the A440 steel joints. The horizontal line extending across the graph at $F_v = 15$ ksi represents the working stress level according to the AISC specifications for friction-type connections[13]. The horizontal line at $F_v = 20$ ksi. would apply for connections subjected to static plus wind loading and in which a one-third increase in allowable stress is permitted. The height of each bar indicates the average bolt shear stress at slip. The relatively low slip resistance of joint E41b has been attributed to warping during the bolting-up operation.

The average slip coefficient of 0.32 obtained in these A440 tests is but slightly less than the values obtained in the similar A7 series (0.35)[2,3]. With this result, coupled with the fact that no joints slipped below an average stress of 20 ksi, it is clear that these joints also meet the requirements of the specification[14].

9. SUMMARY

These conclusions are based on the results of fourteen tests of large bolted joints of A440 steel connected with A325 high-strength bolts and upon related theoretical analysis.

Many of the conclusions are reinforced by the results of tests of joints of A7 steel connected with A325 bolts. The joints were butt-type plate splices proportioned with the area of the plate material at the net section equal to the shear area of the bolts. The effect of joint length upon the ultimate strength of the connection was investigated and a few tests were conducted to determine the effect of joint width.

1. Joints of A440 steel with up to four A325 fasteners in line were capable of developing about 96% of the shear strength of a single bolt (Fig. 8). This result did not differ significantly from the shear strength of A325 bolts in similar A7 steel joints.

2. In joints with more than four fasteners in line, the differential strains in the connected material caused the end bolts to shear before all bolts could develop their full shearing strength. At seven fasteners in line (24.5-in.) about 87% of the shear strength of a single bolt was developed. This decreased to about 80% for a joint with sixteen fasteners in line (52.5-in.) as shown in Fig. 8. As can be seen in Fig. 9 this decrease was not nearly as great as was experienced in A7 steel joints.

3. Good agreement was obtained between the test results and the theoretical analysis. When the tension-shear deformation relationship of the bolts was considered the computed strength was within 3% of the test results.

4. An increase in joint width had no appreciable effect on the ultimate strength of the joint. Evidently the lateral forces due to necking in the plate material were not as serious as was the case with earlier tests of A7 steel joints[2].

5. The presence or absence of washers under the bolt head and nut had no appreciable effect on the behavior of the joint. Any differences between the test joints could be attributed directly to the variations in the bolt shear strengths as reported in Table 5.

6. Controlled variation in the plate area at the net section affected the bolt shear strength as would be expected. As the plate area increased greater rigidity was achieved and corresponding higher shear strength of the bolt groups resulted.

7. The experimental and analytical results suggest that the allowable stress to be used in long A440 steel joints might well be higher than that permitted for similar A7 steel joints.

8. All bolts were tightened by the turn-of-nut method and consistently had preloads approximately 1.3 times the proof load of the bolt.

9. These tests gave mean coefficient of slip for tight mill scale faying surfaces of $K_s = 0.32$. Neither joint length or width had any appreciable effect on the slip coefficient.

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NOMENCLATURE

1. Symbols

A_n — The net tensile area of the plate

A_s — The bolt shear area (for butt-type splices there are two shear planes)

T/S — Ratio of the tensile stress on the net section of plate to the shear stress on the nominal area of the fasteners (A_s/A_n)

U — The unbuttoning factor - defined as the ratio of the average bolt shear stress in the connection when the first bolt shears to the ultimate strength of a single bolt of the same lot and of the same grip

σ_n — The ultimate tensile stress on the net section

τ_{av} — The average bolt shear stress in the bolted connection at failure

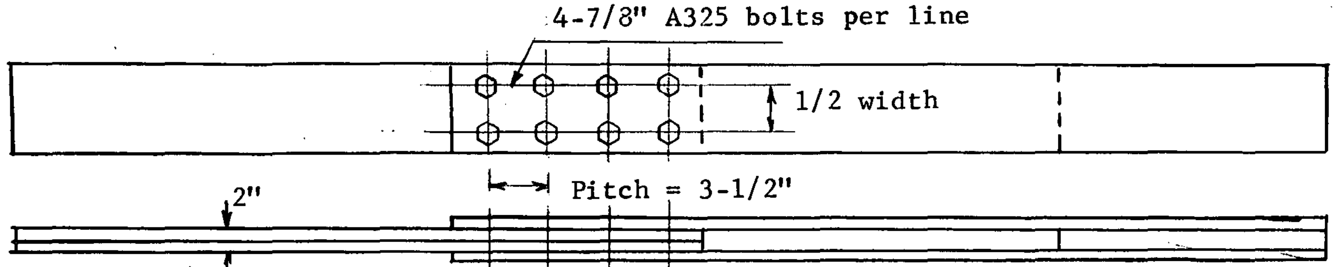
τ_c — The shear strength of a single bolt subjected to double shear by plates loaded in compression

τ_t	The shear strength of a single bolt subjected to double shear by plates loaded in tension

2. Glossary

Gage	The transverse spacing of the bolts
Grip	The thickness of the plate material in the connection
Pitch	The longitudinal spacing of the bolts
Prying Action	The tendency for the lap plate ends to bend out due to the bearing condition
Slip Coefficient	$K_s = P_s/m\sum T_i$, where P_s is the major slip load, m the number of slip planes and $\sum T_i$ = sum of the initial bolt tensions
Snug	The expression used to describe the tightness of a bolt before beginning the turn of the nut. "Snug" is indicated by the impact wrench when impacting begins.
Unbuttoning	The sequential failure of fasteners which progresses from the ends of a joint inward

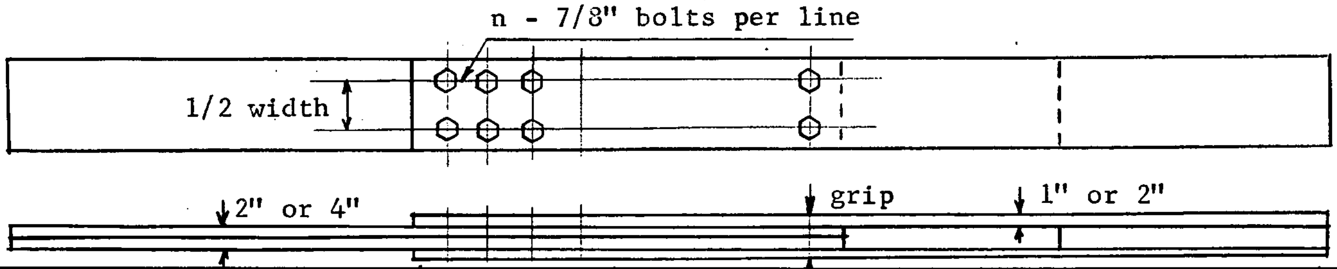
TABLE 1: NOMINAL DIMENSIONS AND TEST RESULTS: PILOT TESTS



ITEM	UNITS	E41a	E41b	E41c	E41e	E41f*	E41g*
BOLTS - Regular Head							
Nominal Shear Area	in^2	9.62	9.62	9.62	9.62	9.62	9.62
Washers Used	-	2	2	2	2	1	0
PLATES							
Mean Width	in.	6.12	6.42	6.59	7.15	6.66	6.68
Mean Thickness (two plates)	in.	2.01	2.01	2.01	2.02	2.00	2.01
Mean Gross Area	in^2	12.31	12.87	13.25	14.43	13.34	13.43
Mean Net Area	in^2	8.54	9.11	9.49	10.65	9.58	9.66
$A_s:A_n$ (T:S)							
Nominal	-	1:0.90	1:0.95	1:1.00	1:1.10	1:1.00	1:1.00
Actual	-	1:0.89	1:0.95	1:0.99	1:1.11	1:1.00	1:1.00
SLIP LOAD (TEST)	kips	262	198	260	282	270	282
Bolt Shear Stress	ksi	27.2	20.6	27.0	29.3	28.1	29.3
Avg. Ext. of Bolts	in.	0.0389	0.0399	0.0333	0.0463	0.0364	0.0392
Clamping Force Per Bolt	kips	51.1	51.2	50.3	51.6	48.3	51.2
Slip Coefficient	-	0.32	0.24	0.32	0.34	0.35	0.34
TYPE OF FAILURE		Plate	All bolts sheared	All bolts sheared	All bolts sheared	All bolts sheared	All bolts sheared
LOAD AT FAILURE	kips	730	754	770	782	727	767
Bolt Shear Stress	ksi	75.9	78.4	80.1	81.3	75.6	79.8

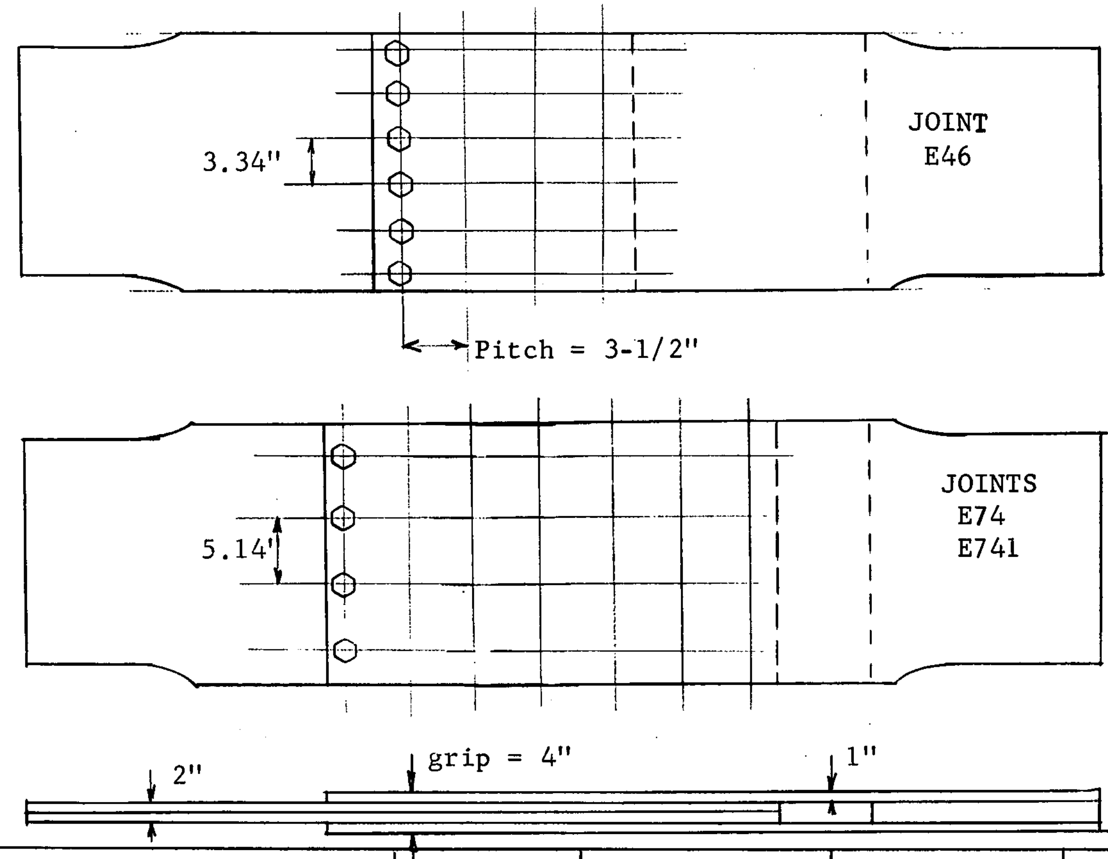
* These connections had heavy head bolts; in all connections the threads were excluded from the shear plane.

TABLE 2: NOMINAL DIMENSIONS AND TEST RESULTS: LONG JOINTS



ITEM	UNITS	E41	E71	E101	E131	E161
BOLTS - Heavy Head, 1 Washer						
No. in Line	-	4	7	10	13	16
Nominal Shear Area	in^2	9.62	16.83	24.04	31.25	38.46
PLATES						
Grip (excluding washer)	in.	4.04	4.00	4.00	7.96	7.98
Mean Width	in.	6.67	10.28	13.88	9.67	11.47
Mean Thickness	in.	2.02	2.00	2.00	3.98	3.99
Mean Gross Area	in^2	13.49	20.56	27.79	38.53	45.67
Mean Net Area	in^2	9.70	16.81	24.04	31.06	38.23
$A_s:A_n$ (T:S)						
Nominal	-	1:1.00	1:1.00	1:1.00	1:1.00	1:1.00
Actual	-	1:1.01	1:1.00	1:1.00	1:0.99	1:0.99
SLIP LOAD (TEST)	kips	250	400	614	824	1028
Bolt Shear Stress	ksi	26.0	23.8	25.5	26.4	26.7
Avg. Ext. of Bolts	in.	0.0406	0.0361	0.0453	0.0552	0.0570
Clamping Force Per Bolt	kips	48.6	48.3	48.9	48.1	48.2
Slip Coefficient	-	0.32	0.30	0.31	0.33	0.33
TYPE OF FAILURE	-	All bolts sheared	One bolt sheared	One bolt sheared	One bolt sheared	One bolt sheared
LOAD AT FAILURE	kips	728	1188	1610	2125	2545
Bolt Shear Stress	ksi	75.7	70.6	67.0	68.0	66.2

TABLE 3: DIMENSIONS AND TEST RESULTS: WIDE JOINTS



ITEM	UNITS	E46	E74	E741
BOLTS - Heavy Head, 1 Washer				
Nominal Shear Area	in^2	28.85	33.67	33.67
PLATES				
Mean Width	in.	20.04	20.57	20.55
Mean Thickness	in.	2.03	1.99	2.01
Mean Gross Area	in^2	40.62	40.99	41.22
Mean Net Area	in^2	29.22	33.51	33.70
$A_s:A_n$ (T:S)				
Nominal	-	1:1.00	1:1.00	1:1.00
Actual	-	1:1.01	1:1.00	1:1.00
SLIP LOAD (TEST)	kips	798	912	680
Bolt Shear Stress	ksi	27.7	27.1	20.2
Avg. Ext. of Bolts	in.	0.0456	0.0403	0.0360
Clamping Force Per Bolt	kips	48.9	48.6	48.3
Slip Coefficient	-	0.34	0.34	0.25
TYPE OF FAILURE	-	All bolts sheared	One bolt sheared	One bolt sheared
LOAD AT FAILURE	kips	2180	2410*	2250
Bolt Shear Stress	ksi	76.5	71.6	66.9

* Earlier fracture of the plate occurred at a load of 2240 kips

TABLE 4: PROPERTIES OF PLATE

Test Series	Number of Coupons	Static Yield Stress, ksi Mean	Static Yield Stress, ksi Std. Dev.	Yield Stress, ksi* Mean	Yield Stress, ksi* Std. Dev.	Ult. Ten. Str., ksi Mean	Ult. Ten. Str., ksi Std. Dev.	% Elong. in 8 inches	% Reduction in area
Pilot	10	43.0	1.17	45.3	1.15	75.4	1.71	28.9	64.5
All Others	30	42.9	0.73	45.3	0.70	76.0	1.01	27.7	61.7
Combined	40	42.9	0.84	45.3	0.82	75.8	1.22	28.0	62.4

* Taken at a 0.2% strain

TABLE 5: PROPERTIES OF 7/8-in. BOLTS

Used in Joints	Bolt Lot	Length Under Head, inches	Thread* Length, inches	Direct Tensile Strength, kips			Torqued Tensile Strength, kips			Compression Shear Strength, τ_c, ksi			Tension Shear Strength τ_t, ksi		
				No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.
E41a,b, c,e	D	5.5	2	5	56.9	0.55	4	51.1	0.77	3	88.9	1.14	3	84.4	1.95
E41g	8A	5.25	1.5	5	59.4	1.11	5	52.2	1.91	3	85.1	2.00	3	82.0	0.54
E41f & E41-E101	8B	5.5	1.5	5	55.5	1.12	5	49.3	1.68	3	86.1	1.46	3	76.9	1.78
E131, E161	H	9.5	1.75	7	58.3	1.28	6	48.3	1.69	3	86.0	2.04	3	79.2	0.46

* There were no threads in the shearing planes

TABLE 6: COMPARISON OF TEST RESULTS AND COMPUTED STRENGTH

JOINT	COMPUTED ULTIMATE STRENGTH, KIPS			LOAD AT FAILURE KIPS
	Method 1 Compression Jig	Method 2 Tension Jig	Method 3[+] Combined	
E41	806	729	-	728
E41f	806	729	-	727
E41g	800	776	-	767
E71	1282	1178	1200	1188
E101	1696	1588	1612	1610
E131	2163	2062	2102	2125
E161	2599	2496	2538	2545

[+] The bolts in the end two rows at each end of the joint, were assumed to be represented by the tension shear-deformation relationship. The remaining bolts by the compression shear-deformation relationship.

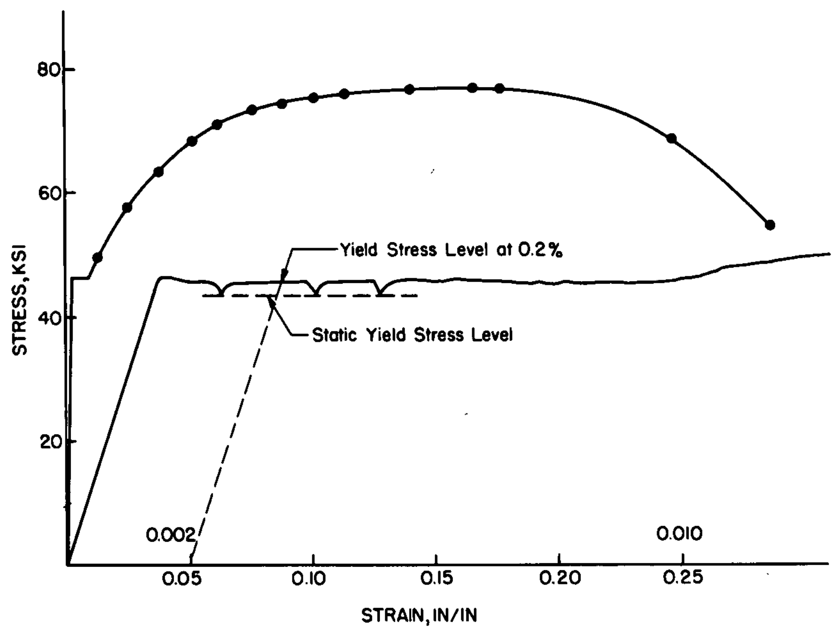


FIG. 1 TYPICAL STRESS-STRAIN DIAGRAM FOR PLATE MATERIAL

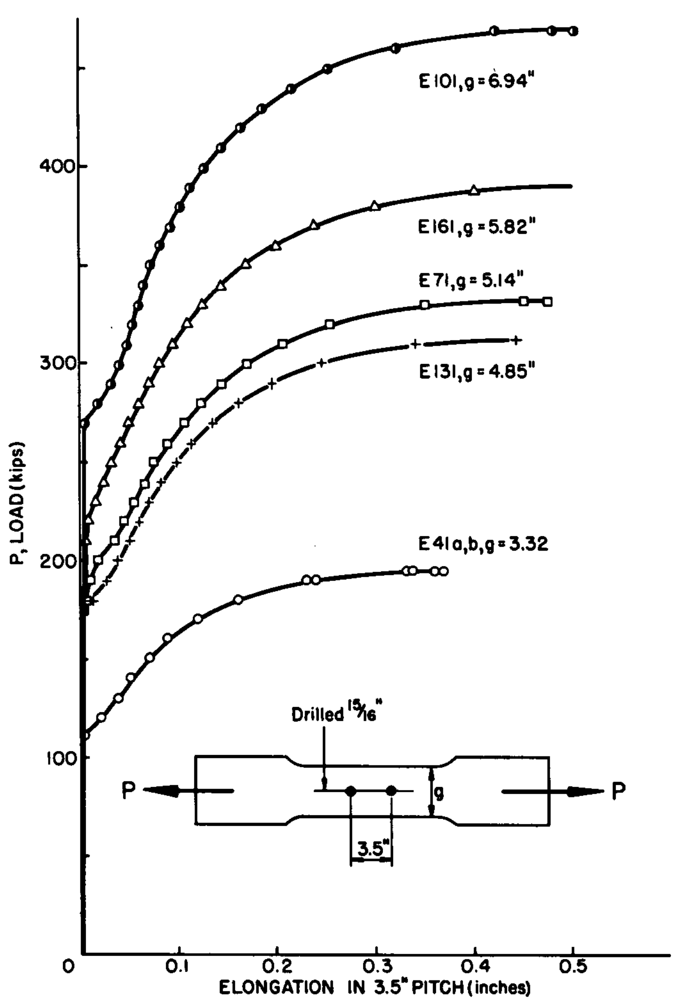


FIG. 2 RESULTS OF PLATE CALIBRATION TEST

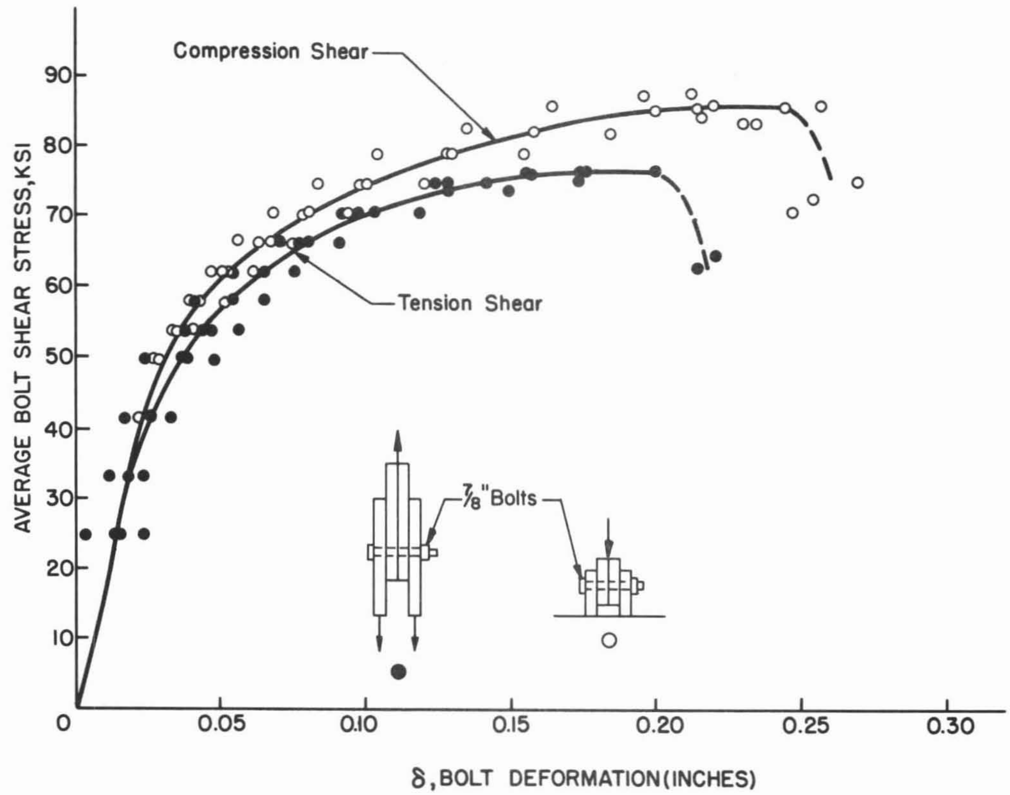


FIG. 3 SHEAR-DEFORMATION RELATIONSHIP FOR A325 BOLTS IN A440 STEEL

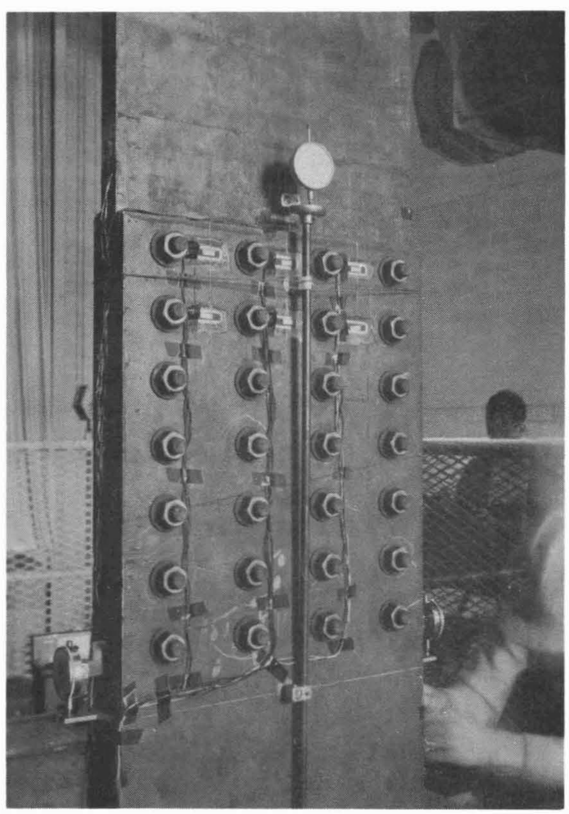


FIG. 4 JOINT MOUNTED IN TESTING MACHINE WITH INSTRUMENTATION ATTACHED

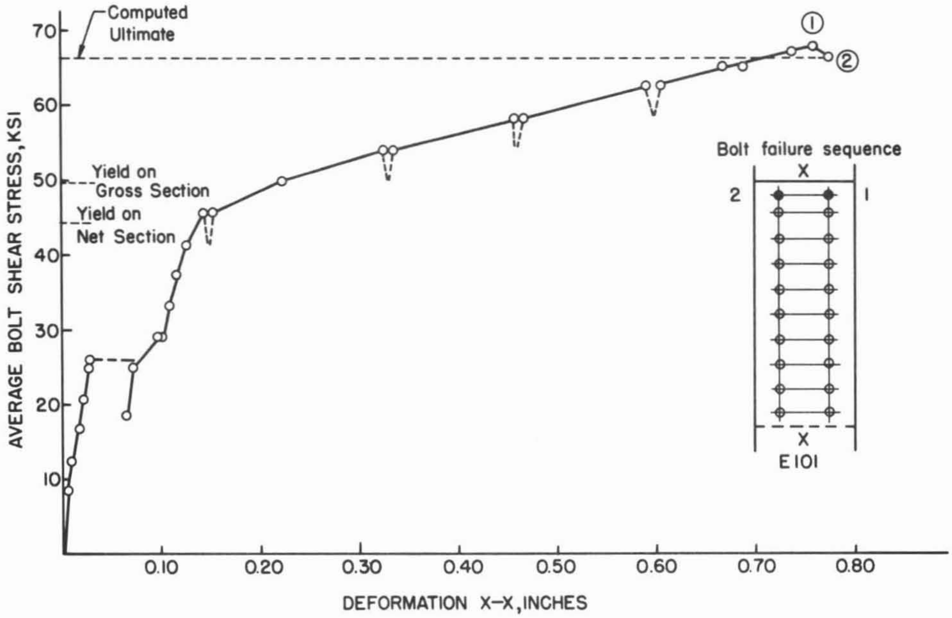


FIG. 5 TYPICAL LOAD-DEFORMATION CURVE

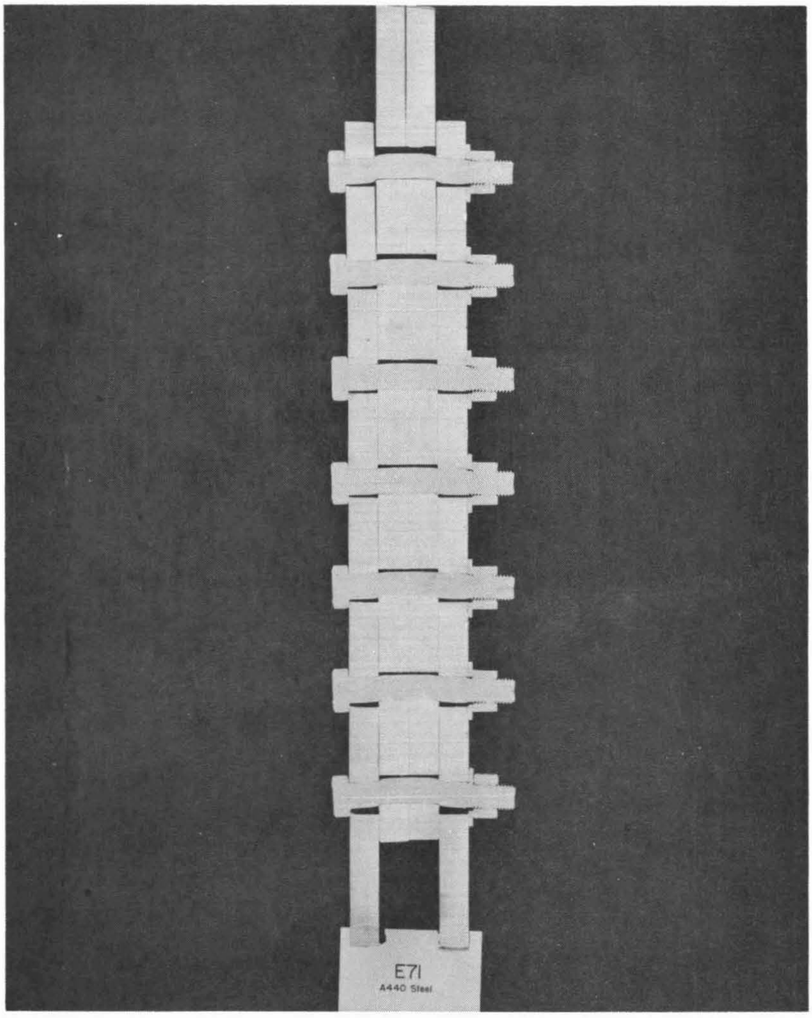


FIG. 6 SAWED SECTION OF JOINT E71

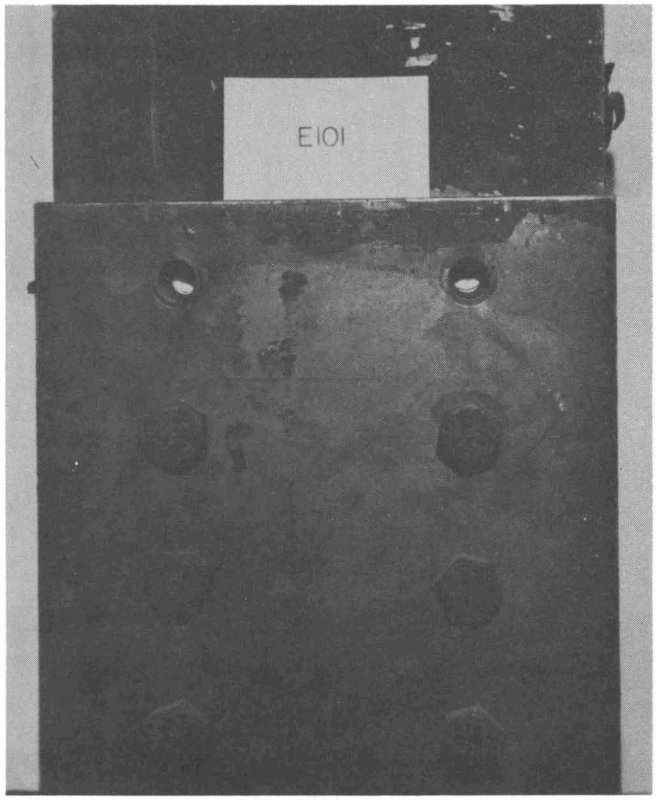


FIG. 7 JOINT E101 SHOWING SHEARED BOLT SHANKS AFTER UNBUTTONING

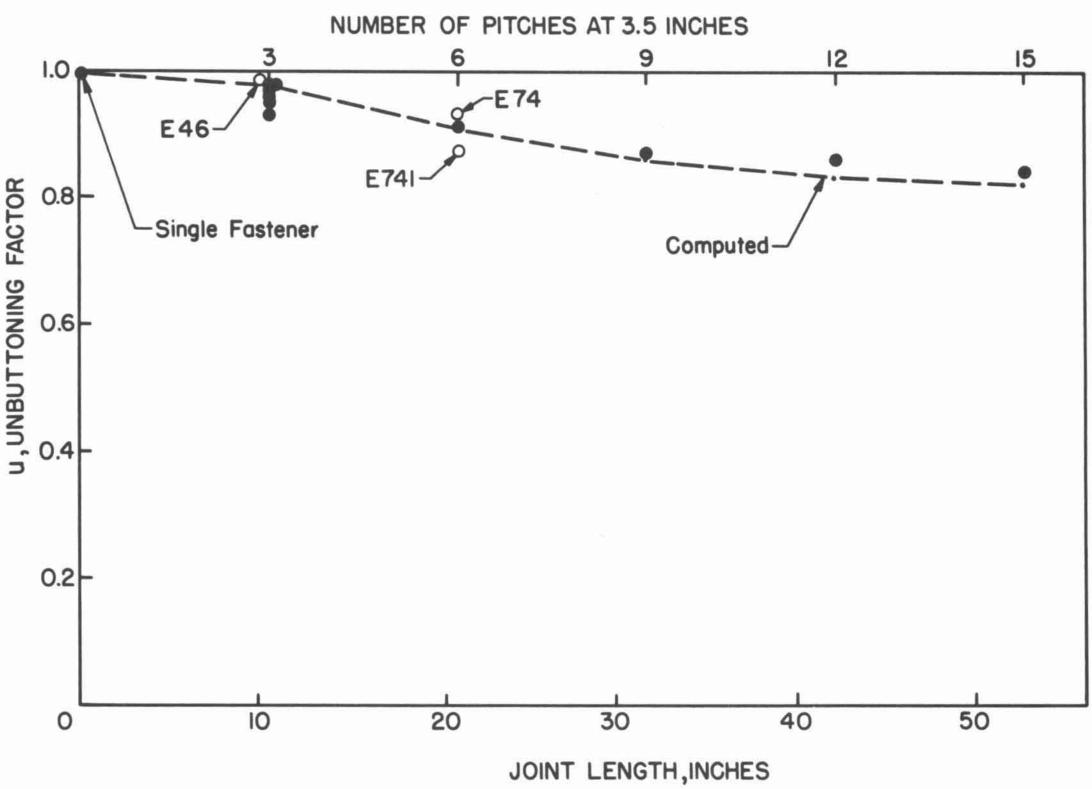


FIG. 8 EFFECT OF JOINT LENGTH ON THE UNBUTTONING FACTOR

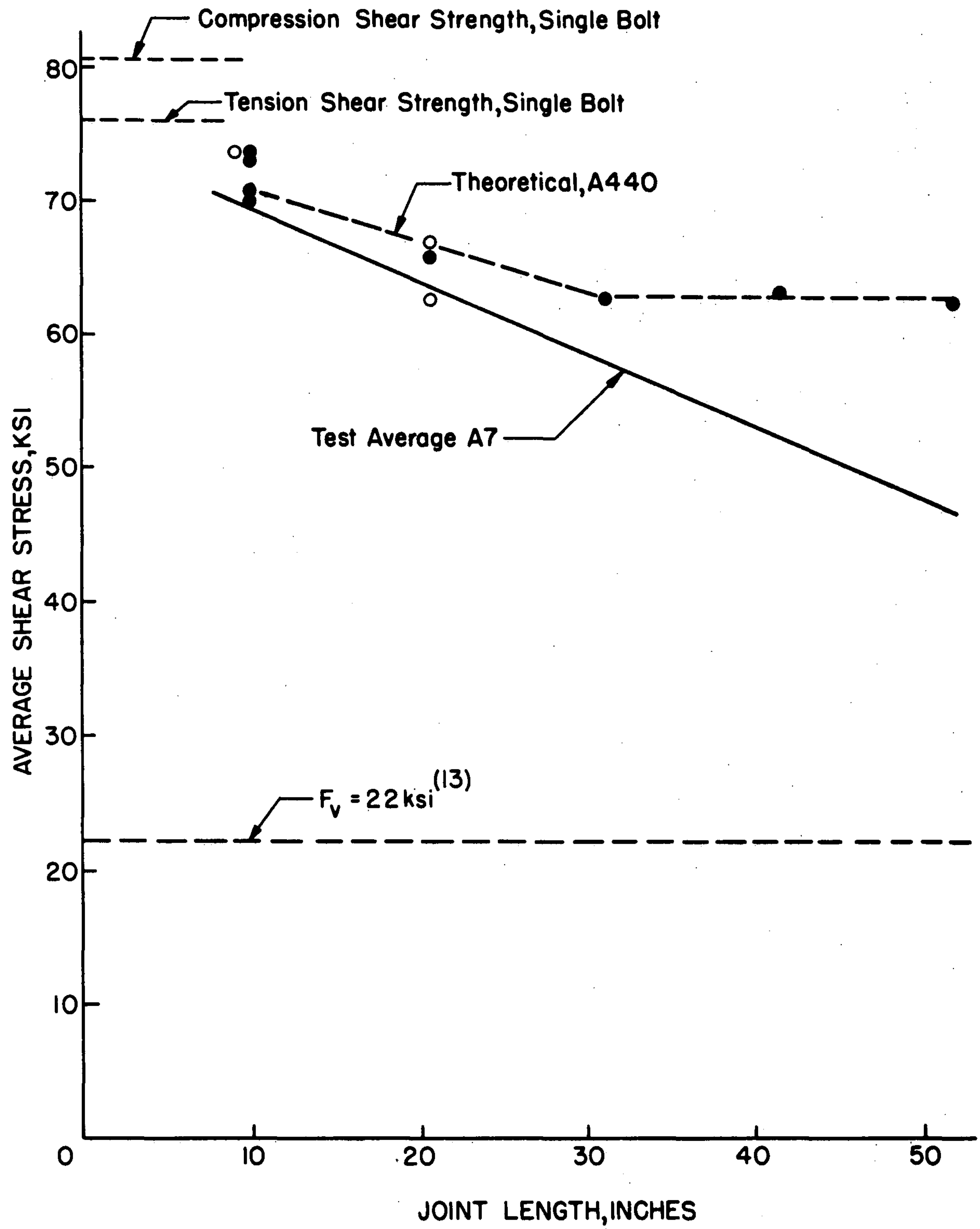


FIG. 9 COMPARISON OF A440 STEEL BUTT JOINTS AND A7 STEEL BUTT JOINTS

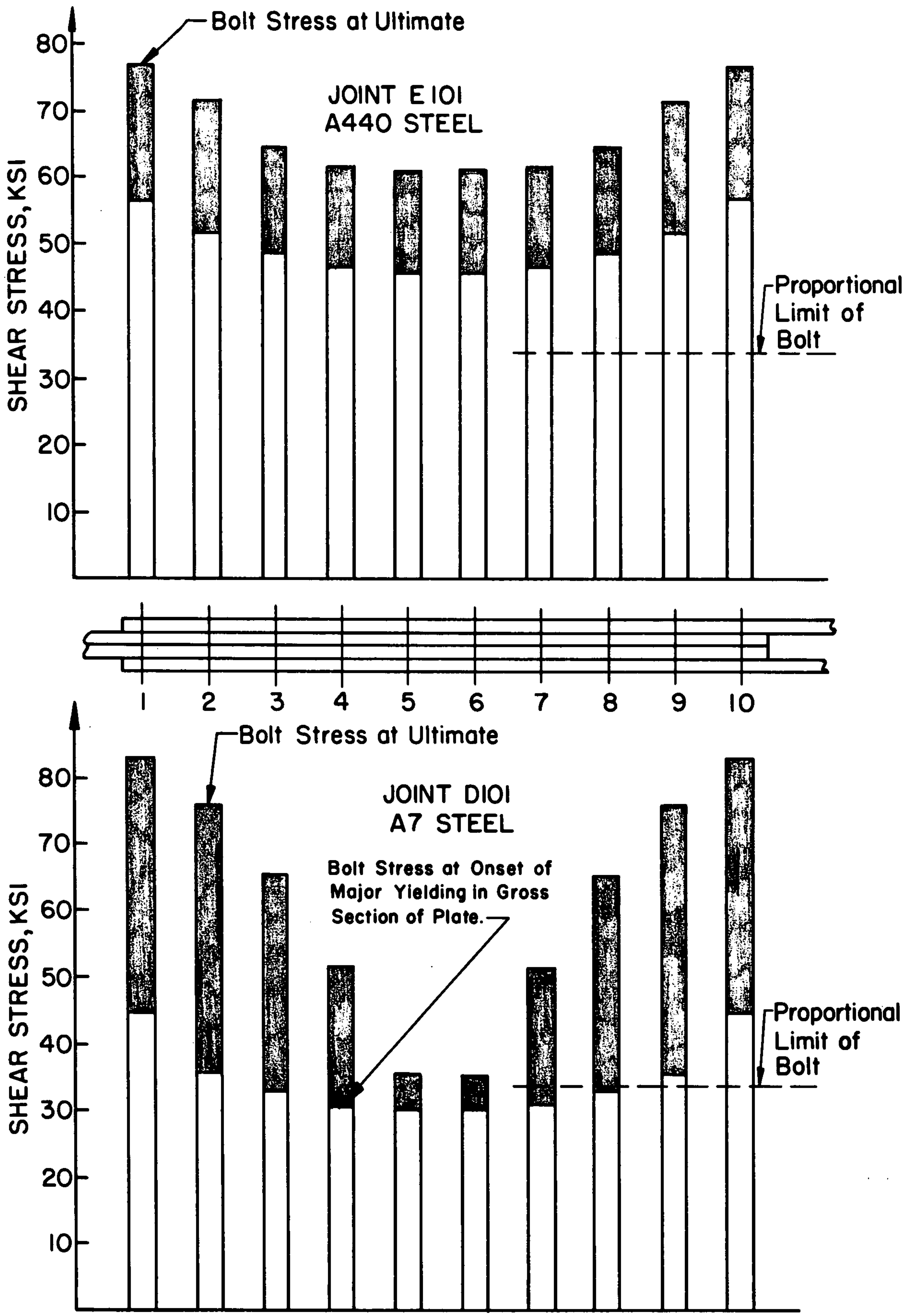


FIG. 10 LOAD PARTITION IN BOLTED JOINTS

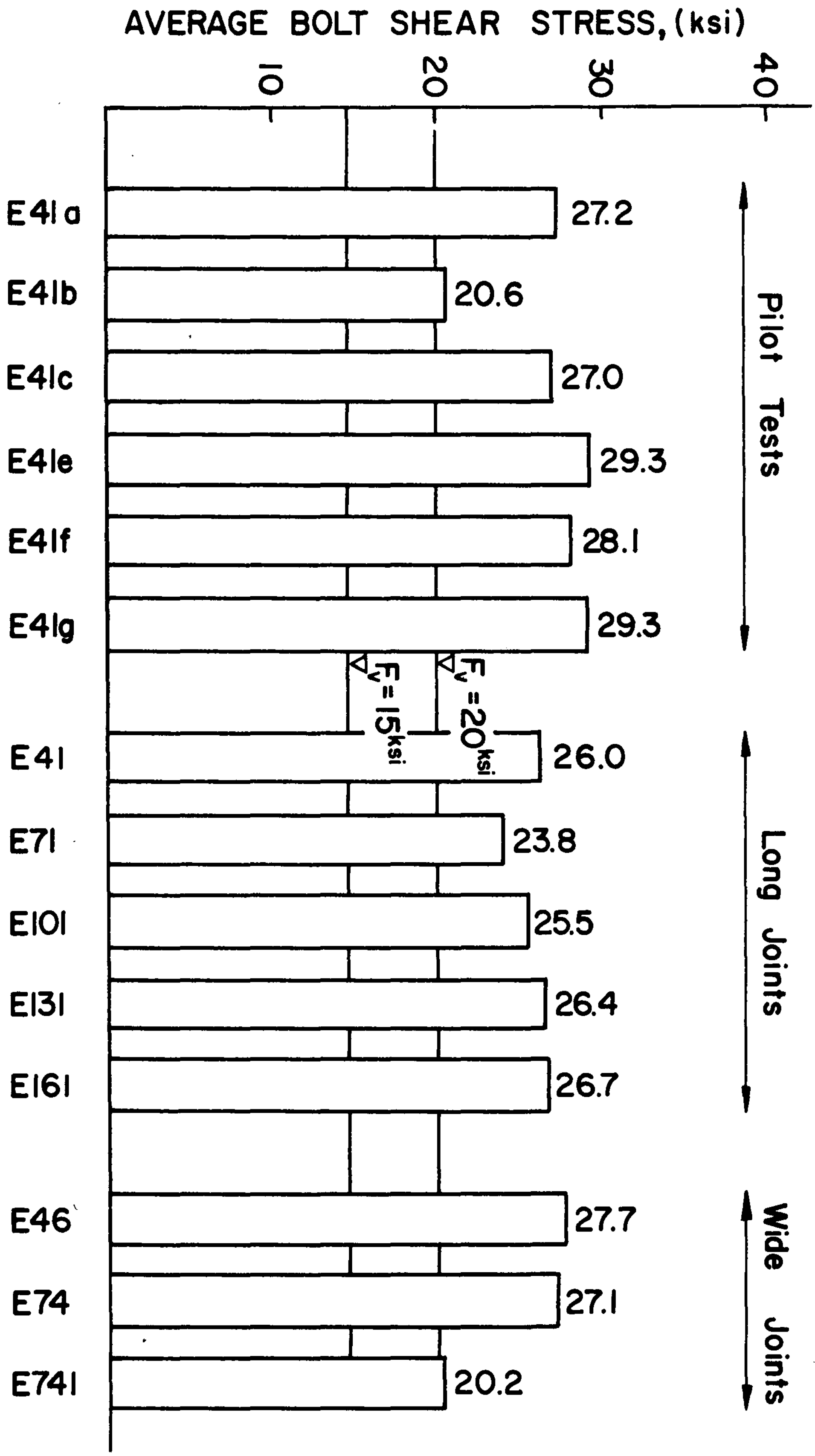


FIG. 11 SLIP RESISTANCE OF BOLTED JOINTS TIGHTENED BY TURN-OF-NUT METHOD

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