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LEHIGH UNIVERSITY INSTITUTE OF RESEARCH

Large Bolted Connections

TESTS OF LONG A440 STEEL BOLTED BUTT JOINTS

by

Gordon H. Sterling
John W. Fisher

Fritz Engineering Laboratory Report No. 288.26

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This work was carried out as part of the Large Bolted Connections Project sponsored financially by the Pennsylvania Department of Highways, the Department of Commerce - Bureau of Public Roads, the American Institute of Steel Construction, and the Research Council on Riveted and Bolted Structural Joints.

Fritz Engineering Laboratory
Department of Civil Engineering
Lehigh University
Bethlehem, Pennsylvania

February 1965

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SYNOPSIS

Four tests of long structural joints of A440 steel, connected with A325 high strength bolts installed by the turn of the nut method, were conducted to determine their slip resistance and ultimate strength. The primary objective of the test series was to substantiate the results of recent theoretical and analytical studies(1).

All of the joints had two lines of fasteners, with 7 in line for two of the specimens and 16 in line for the remaining two.

These studies, together with earlier work, have shown that the theoretical analysis presented in Reference 1 gives an accurate prediction of the ultimate joint load.

INTRODUCTION

Several tests of A440 steel joints fastened with A325 bolts have been conducted at Fritz Laboratory, Lehigh University. The results of most of these tests have been reported in a recent publication(1). More tests were deemed necessary to substantiate some of the analytical studies(2) recently completed.

This report gives the results of these additional tests. The data from these tests have not yet been made generally available, although the results were briefly mentioned in a recent report(2).

DESCRIPTION OF TEST SPECIMENS

In the previous series of tests of large bolted joints the ratio of net plate area (A_n) to total bolt shear area (A_s) was maintained at a constant value of 1.0. In the tests reported herein both the A_n/A_s ratio and the number of bolts in line were varied. Two of the joints tested had an A_n/A_s ratio of 0.8, the ratio for the remaining two being 1.2. Two joints had 2 lines of bolts with 7 bolts per line. The other two joints had 2 lines of bolts with 16 bolts per line.

The pitch length was 3-1/2 inches for all four joints. This corresponded to joint lengths of 21 inches and 52-1/2 inches for the 7 bolts in line and 16 bolts in line joints respectively. The joints with 16 bolts in line were fastened with 9-1/2 inch bolts, with a nominal grip of 8 inches. Those with 7 bolts in line used 5-1/2 inch bolts with a nominal 4 inch grip.

Table 1 gives the geometrical properties of each joint tested.

MATERIAL PROPERTIES

The A440 steel plate used in these joints was from the same heat used for the previous tests(1). This plate material had an average static yield stress of 43 ksi and a ultimate strength of 76 ksi. The behavior of plate elements with holes was predicted by the method outlined in Ref. 2. Consequently, no actual calibration tests of plates with holes were required.

The A325 bolts, designated as lots 8B and H for the 5-1/2 inch and 9-1/2 inch bolts respectively, had been calibrated in both direct and torqued tension(3), and in double shear(4). These fasteners had also been used in the earlier tests(1).

FABRICATION AND ASSEMBLY

The plate elements were flame cut to rough size and milled to final dimensions. All oil and grease was removed from the plates to establish a clean faying surface.

Alignment of holes was assured by clamping together all plates in a particular joint, and then drilling through the entire assembly. All holes were drilled to 15/16 inch diameter to allow 1/16 inch clearance for the 7/8 inch diameter bolts.

The bolting up operation was done at Fritz Laboratory by technicians on the lab staff under the supervision of the engineers on the Large Bolted Connections project. The bolts were installed by the turn-of-the-nut method. All bolts were installed by turning 1/2 turn from snug.

The bolt elongations at 1/2 turn were measured. These data were related to the load-deformation curves of the particular bolt lot to determine the initial preload in each bolt. From this information the clamping force on each joint could be readily determined.

INSTRUMENTATION

The instrumentation used was similar to that described in previous work(1). A brief description of all major types of instrumentation is given below. A schematic representation of the instrumentation is given in Figures 1 and 4.

SR 4 electric resistance strain gages were attached to the edges of each plate. These gages were used to detect eccentricity of loading caused by uneven gripping, or by curvature in the joint.

The elongation of each pitch in the joint was measured along the edges of the plates with a mechanical slide-bar extensometer.

Dial gages, reading to the nearest 0.001 inches, were used to measure the joint elongation. More sensitive gages, reading to the nearest 0.0001 inches, were used to measure the slip between the lap and main plates.

TEST PROCEDURE

As was mentioned previously, the primary purpose of these tests was to determine the ultimate load value for the joint. However, particular care was taken to determine the pre-slip behavior of these joints.

After the specimen had been mounted in the testing machine and fitted with instrumentation, a low gripping load of 50 kips was applied. Load was then increased in increments of 50 kips until the joint was carrying about 80% of its expected slip load. During the loading both slip and joint elongation measurements were taken to determine the load-deformation characteristics of the joints.

After reaching about 80% of the expected slip load, the loading cycle was reversed and the load was removed in increments of 50 kips, back to the initial gripping value. Again, load-deformation data were taken at each load increment. Load was then re-applied to a value equal to or above the load of the first cycle.

This type of cyclic loading was applied to joints E722, E163, and E164. Joint E721 slipped before expected during the first loading cycle. Joints E722 and E163 were loaded so that slip occurred on the second loading cycle. Joint E164 was unloaded twice and was caused to slip during the third loading cycle.

As load was applied beyond the major slip load the elastic and inelastic plate deformations were recorded at specific increments by the strain gage readings, the slip and joint elongation dials, the pitch elongation readings and by visual observations.

Two days were required to test joints E163 and E164. In both cases the load attained on the first day had caused the net section to yield. The load was reduced to a relatively low value overnight, as is shown in Fig. 2. On the second day these joints were reloaded to the highest load of the previous day. Testing then proceeded as usual until failure occurred

TEST RESULTS

The major results are summarized in Table 1.

Joint E721, with an A_n/A_s ratio of 0.8, slipped into complete bearing under a load of 366 kips as is shown in Figures 1 and 4. This load corresponded to a slip coefficient of 0.28, and an average "bolt shear stress" at slip of 21.7 ksi. This joint reached an ultimate load of 1070 kips, which was 8 kips below the predicted load, and failed by unbuttoning of a bolt at the main plate end, as is shown in Figure 3a.

Despite the care taken in fabrication and assembly joint E722 had considerable curvature, convex on the east (or nut) side of the joint. As load was applied to the specimen the joint elongation dials showed that the east side actually shortened under initial loading. This fact is shown in Fig. 5. Also, the strain gage readings indicated that the east side of the joint had gone into compression under the initial loading. As the loading continued the west side of the specimen elongated much more than the east side. At the major slip load the west lap plate slipped 0.072 inches (i. e. into bearing), whereas the east lap plate moved only 0.039 inches. Strain gage readings taken just prior to major slip showed that over 55% of the load was being transferred through the west side of the joint.

The major slip load was taken as 328 kips, and for consistency the slip coefficient was calculated on an assumed symmetrical load distribution. This gave a slip coefficient of 0.24 and a average "bolt shear stress" at slip of 19.4 ksi. It is apparent that these low values were caused by unsymmetrical load transfer within the joint, resulting from the curvature of the specimen.

E722 was the only joint of this series which was warped in this manner. Strain gage readings taken on E721, E163, and E164 indicated that the load was being transferred symmetrically in these joint just prior to slip.

Joint E722 failed by a sudden shearing of all bolts at an ultimate load of 1270 kips. This failure mode is shown in Fig. 3b. Evidence of considerable lap plate prying is indicated by two features: (1) the lap plates are bowed outwards from the main plate, and (2) the nut side of one of the lap plate end bolts did not shear. This indicates that, as the heads of the bolts at the lap plate end sheared, the outward prying action caused the shank of this one bolt to be pulled out of the main plate hole before it could be sheared. When one realizes that this joint failed within a fraction of a second, the magnitude of this outward prying action becomes apparent.

Joint E163 slipped under an applied load of 796 kips. The slip was very sudden, and all bolts in the joint were taken into complete bearing. The 796 kip load corresponded to a slip coefficient of 0.27 and a average "bolt shear stress" at slip of 20.7 ksi. As is shown in Figure 3c this joint failed by unbuttoning of a fastener at the lap plate end of the joint, under a load of 2180 kips. This load was 100 kips above the predicted value, given in Table 1, and corresponded to an average bolt shear stress of 56.5 ksi at failure.

Figure 6 shows the pre-slip behavior of joint E163. A maximum load of 700 kips was applied during the first load cycle. The joint was then unloaded to 200 kips, as is shown in Figure 6. In order that the deformations measured by the slip and joint elongation dials could be compared the deformations indicated at 200 kips were extrapolated back to zero load, as is shown by the dotted lines in Fig. 6. This indicates that a permanent deformation of 0.006 inches had occurred at the slip dials, as compared to only 0.004 inches measured by the joint elongation dials. This behavior was expected, and is explained in a later section of this report. During the second cycle the loading was continued up to major slip, which occurred at 796 kips.

The load-deformation characteristics of joints E164, as shown in Figures 2 and 7, indicate that the bolts were not taken into bearing at major slip. Both figures clearly show, however, that the point of rigid body movement between lap and main plate is well defined and that there can be no question that major slip occurred at 850 kips.

This joint was loaded to 700 kips during the first load cycle, and then unloaded again to a load of 50 kips. This was repeated one more time, as is shown in Figure 7, and then load was applied until slip had occurred. The residual deformation at zero load, as extrapolated from the 50 kip load, was 0.0032 inches for the slip measurements and 0.0005 inches for the joint elongation measurements. This again followed the same general trend in Fig. 6.

The slip load of 850 kips corresponded to an average "bolt shear stress" of 22.4 ksi and a slip coefficient of 0.29. Table 1 shows that the failure load of 2785 kips was 65 kips above the predicted value. The failure mode, unbuttoning of a lap plate end fastener, is shown in Figs. 3c and 3d.

ANALYSIS OF RESULTS

1. Behavior Prior to Slip

(i) Loading

Figures 4, 6, and 7 show that the slip dials recorded deformations as soon as load was applied to the member. Part of this deformation was caused by elastic elongations in the 3.5 inch gage measurement length. It is apparent from these plots that the measured slip deformations deviated from linearity long before major slip was reached. That is, there was differential movement between the main and lap plate at the joint ends under relatively low loads. Analytical and experimental studies(5) have shown that relative displacements of contact surfaces at the ends of a butt joint should occur before major slip. As the joint load is increased from zero this displacement between discrete contact points proceeds inward from the joint ends as the shear stress on the faying surface exceeds the slip resistance. When the maximum static frictional resistance is reached over the entire faying surface major slip occurs.

Figure 8 shows schematically the shear stress distribution along the faying surface for various joint loads. As the loading is increased the shear stress at the joint ends reaches the maximum static frictional resistance. As additional load is applied to the joint relative movement of the points of contact begins to occur, as is shown in the "slip zone".

This figure shows, qualitatively, that a relative movement of the faying surfaces near a joint end should occur under relatively low loads. The test data have indicated that this does occur.

At higher loads the differential movement between the lap and main plate continues to increase until, at a specific load (the "major slip load"), a sudden movement between all points of contact occurs. This sudden movement is shown clearly in Figures 4 through 7. For joints E163, E721, and E722 this sudden movement was approximately 1/16 inch. That is, the plates slipped until all bolts were in complete bearing. Figure 7 shows that there was a sudden slip of 0.034" in joint E164, but not into complete bearing. However, there was no doubt that major slip had occurred.

In this report, and in other tests(1)(2) the slip load has been taken as the load at which a sudden major movement occurred between every discrete point of contact of the two faying surfaces. Other investigators have reported slip coefficients based on the "first movement of a 1/1,000 inch dial" placed near the ends of the joint(6).

(ii) Unloading

Figures 5, 6, and 7 show that some deformations between the main and lap plate remained when the joint was unloaded. This behavior can be explained qualitatively by reference to Fig. 9. The figure shows a butt joint at various stages of loading. As load is applied to the joint, displacements occur at the joint ends (Fig. 9b) when the shear on the faying surfaces exceeds the statical frictional resistance (Fig. 9c). When the load is removed frictional shearing forces are created as the plates attempt to return to their original positions (Fig. 9d). The resulting residual deformations are shown in Fig. 9e, and two possible shear stress distributions under the unloaded condition are given in Fig. 9f. Several distributions of shear stress are possible, depending on the magnitude of the original load P. These stresses are local in nature, and hence have little effect on the joint deformation readings. This explains why the deformations given by the joint elongation dials, after unloading the joint, were less than those given by the slip dials. (Figs. 6, 7).

2. Joint Slip

Figure 10 shows a bar graph of the slip coefficients attained in these four tests and in the previous tests of similar joints(1). The slip coefficients ranged from 0.24 to 0.29 for the four tests under discussion. This was slightly below the average value attained in the previous work(1).

Also shown is the average "bolt shear stress" at the major slip load for these four joints. All of these tests indicated a slip resistance above the currently specified value of 15 ksi for static loading. Most of the tests gave a slip resistance above the 20 ksi specified(7) for static and wind loading.

3. Ultimate Joint Strength

The ultimate strengths of these joints had been predicted by using the theoretical solution developed in Ref. 2. The predicted values are compared to the actual test results, both in Table 1 and in Figures 1 and 2.

This comparison shows that the ultimate load was predicted very accurately for the two joints fastened with short bolts. The two joints fastened with long bolts, E163 and E164, gave ultimate loads somewhat higher than the predicted value.

In Ref. 2 the ultimate joint load was calculated from the shear strength of a single bolt. The shear calibration procedure was conducted so that the shearing plane was nearly perpendicular to the bolt axes. Fig. 11a shows a side view of the failure mode of joint E721. This illustrates that the center plies of this joint, with short grip bolts, moved together. That is, the shearing of the bolts in this joint was essentially the same as in the calibration process. However, Fig. 11b shows that all plies within joints E163 and E164 moved individually as the ultimate joint load was approached. This action caused the bolts to assume a curved position which provided a larger shear area, with a resulting increase in ultimate shearing strength. (A similar increase in the shear strength of long bolts was obtained for the tests reported in Ref. 8). Since the predicted ultimate load was based on the shear strength of a single bolt, calibrated so that no relative movement of the member plies was allowed, one would expect a very close prediction for the joints with short bolts and a conservative prediction for those joints with long bolts. The data in Table 1 verifies this expectation.

The effect of joint length on the average bolt shear stress at failure is shown in Fig. 12. The theoretical solutions, shown as solid lines, were developed from Ref. 2. This plot confirms the accuracy of the theoretical analysis.

CONCLUSIONS

The results of these tests have supported the conclusions reached in previous studies(1)(2). Also new information concerning the slip behavior of joints has been obtained. The important conclusions are summarized below.

1. As load is applied to a bolted joint differential movement between the lap and main plate will occur at the joint ends under relatively low loads. This movement is expected, and does not indicate that the "major slip load" has been reached.

2. As the loading is increased this differential movement between discrete contact points of the faying surfaces will proceed inward from the joint ends until the maximum static frictional resistance is overcome. At this point a sudden major movement of the entire lap plate with respect to the main plate will occur. This constitutes major slip.

3. These tests gave slip coefficients which varied from 0.24 to 0.29. There was no apparent variation caused by changing joint length or width.

4. The ultimate strength of a bolted joint can be predicted by the method developed in Ref. 2.

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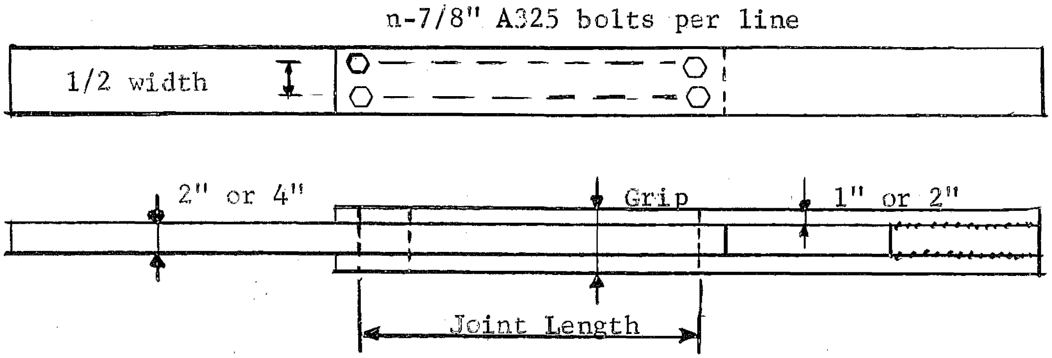
This study has been carried out as a part of the research project on "Large Bolted Connections" being conducted at Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University. Professor W. J. Eney is Head of the Department and Laboratory. Professor L. S. Beedle is Director of the Laboratory.

Technical guidance is provided by the Research Council on Riveted and Bolted Structural Joints through an advisory committee under the chairmanship of Professor J. L. Rumpf.

TABLE 1. TEST RESULTS



Item:	Units	E721	E722	E163	E164
Bolts: 7/8" dia., A325 heavy head, one washer.					
No. in line, n		7	7	16	16
Plates: A440					
Joint width	in.	8.59	12.02	9.60	13.42
pitch	in.	3.50	3.50	3.50	3.50
grip	in.	4.0	4.0	8.0	8.0
joint length	in.	21	21	52.5	52.5
A_n/A_s:					
Design	-	0.80	1.20	0.80	1.20
Actual	-	0.805	1.21	0.805	1.20
Slip Load Test	kips	366	328	796	850
Ave. "Shear Stress" at Major Slip	ksi	21.7	19.4	20.7	22.4
Slip Coefficient	-	0.28	0.24	0.27	0.29
Ultimate Load					
Predicted	kips	1078	1270	2080	2720
Actual	kips	1070	1270	2180	2785
Ratio, $\frac{\text{Predicted}}{\text{Actual}}$		1.007	1.000	.954	.977
Type of Failure	-	One bolt unbuttoned	All bolts sheared	One bolt unbuttoned	One bolt unbuttoned
Ave. Shear Stress at Ultimate Load	ksi	63.5	75.2	56.5	72.2
Ultimate Shear Stress of a single bolt (in a tension jig)	ksi	77.0	77.0	79.0	79.0

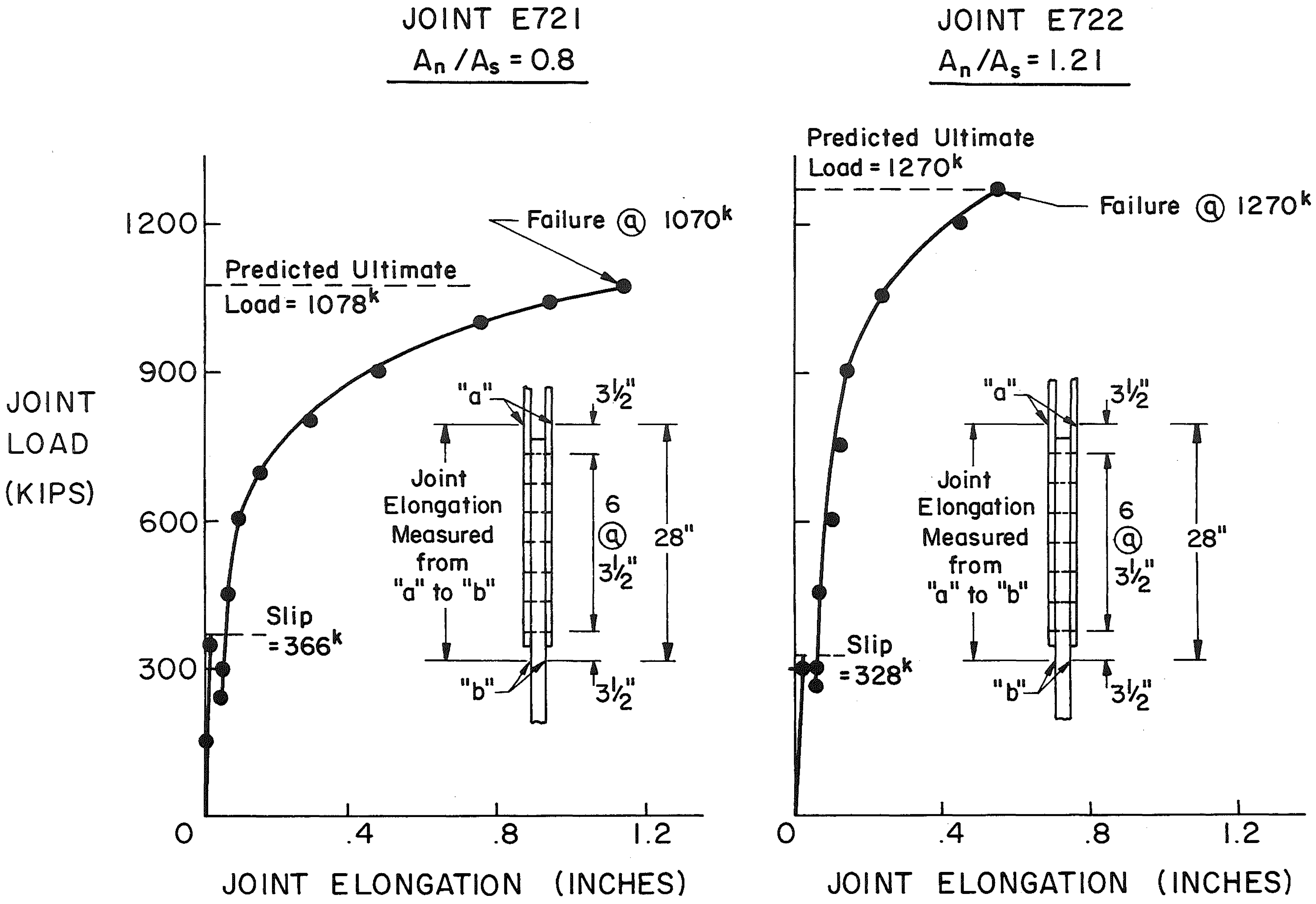


Figure 1. Load-Elongation Characteristics of Joints E721 and E722

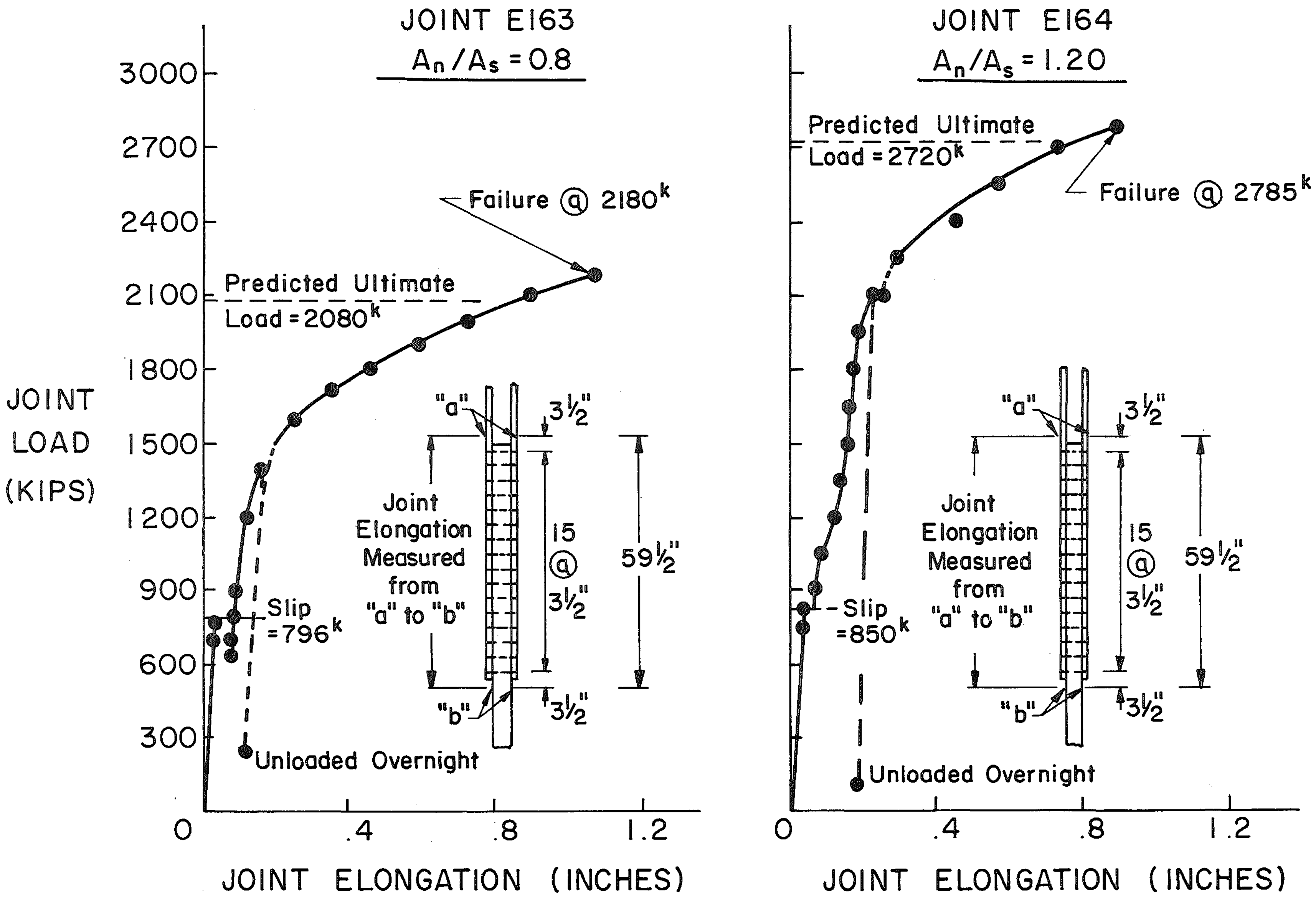
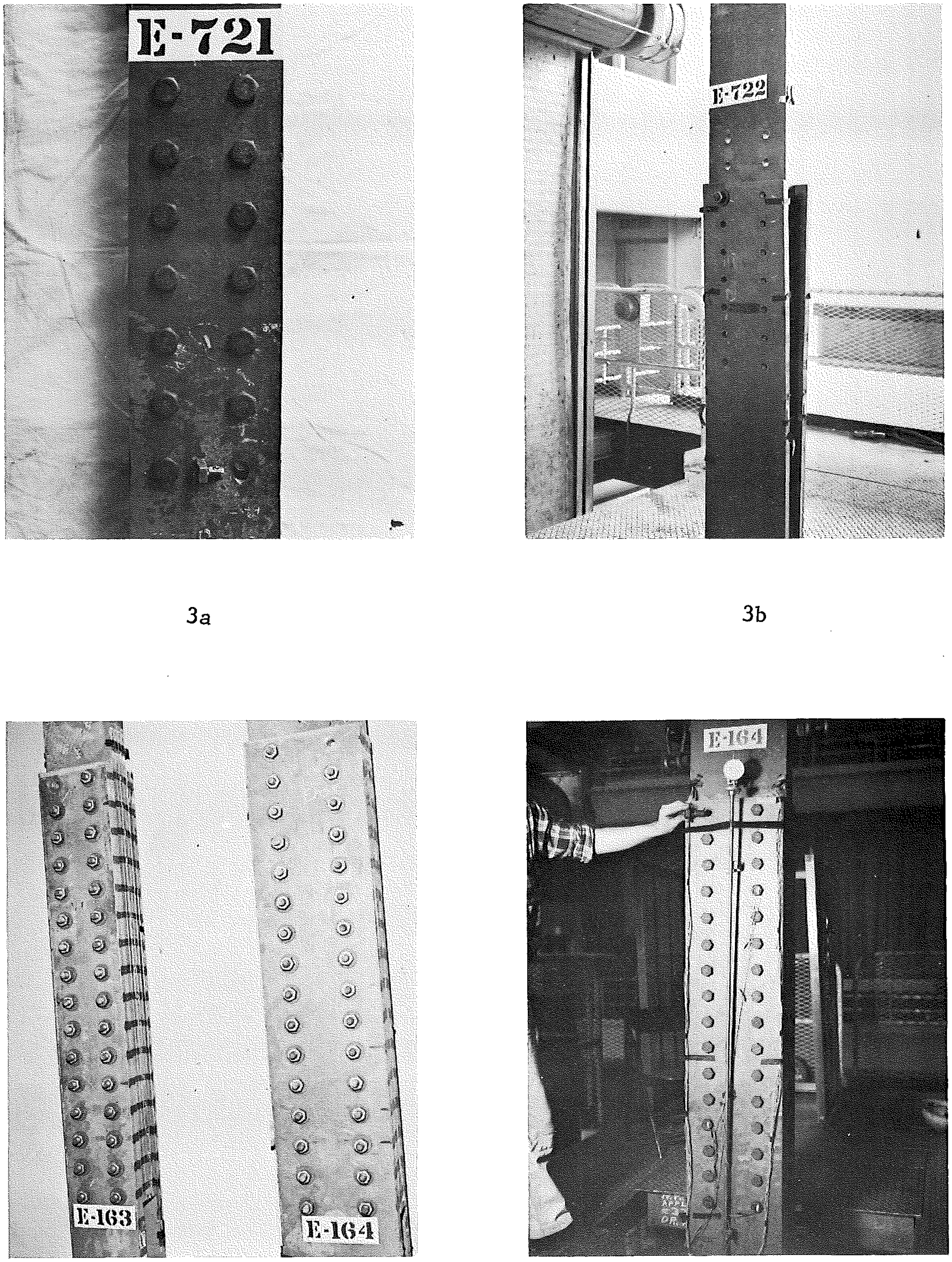


Figure 2. Load-Elongation Characteristics of Joints E163 and E164



3a

3b

3c

3d

Figure 3. Failure Modes of Joints E721, E722, E163, and E164

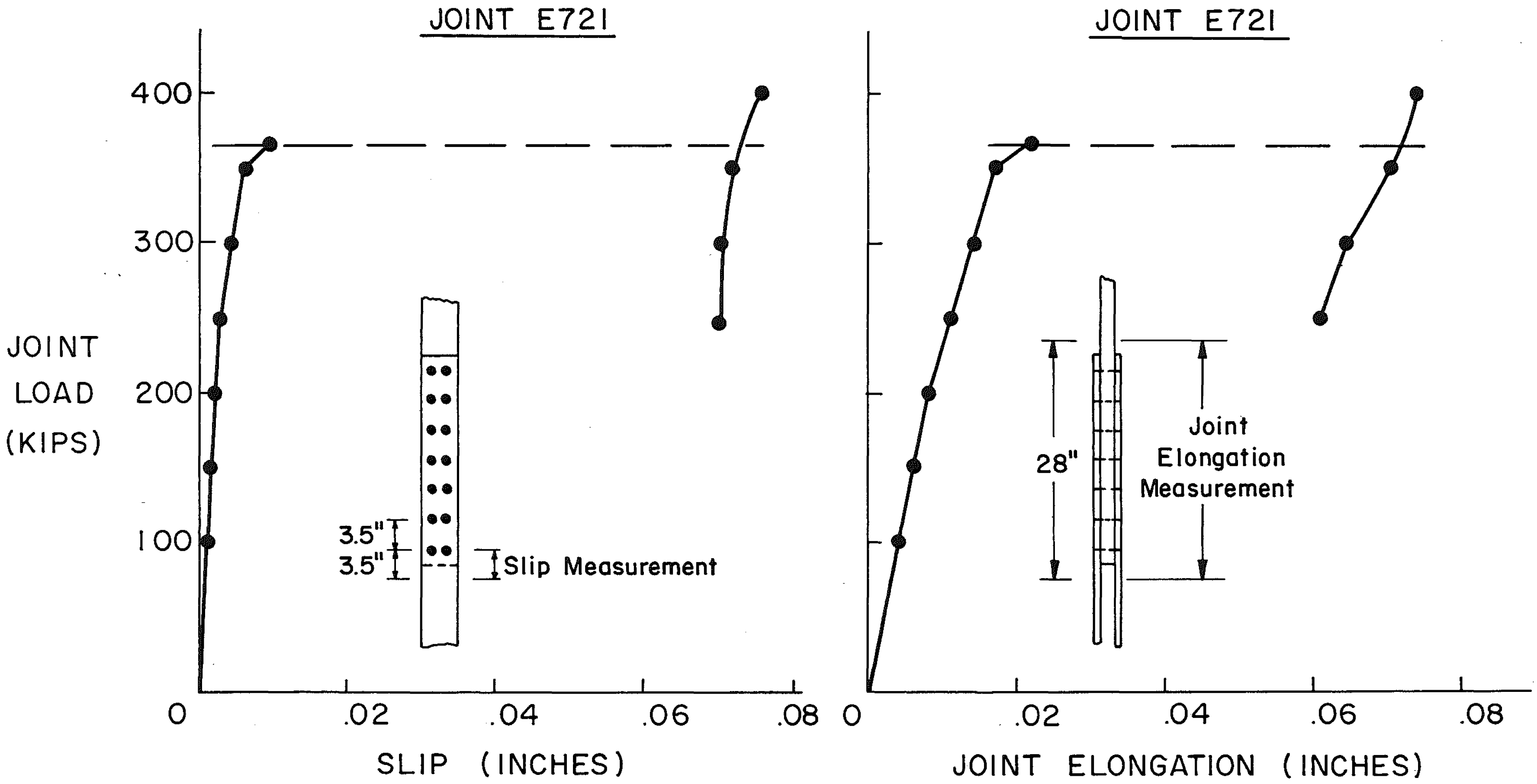


Figure 4. Pre-Slip Behavior of Joint E721

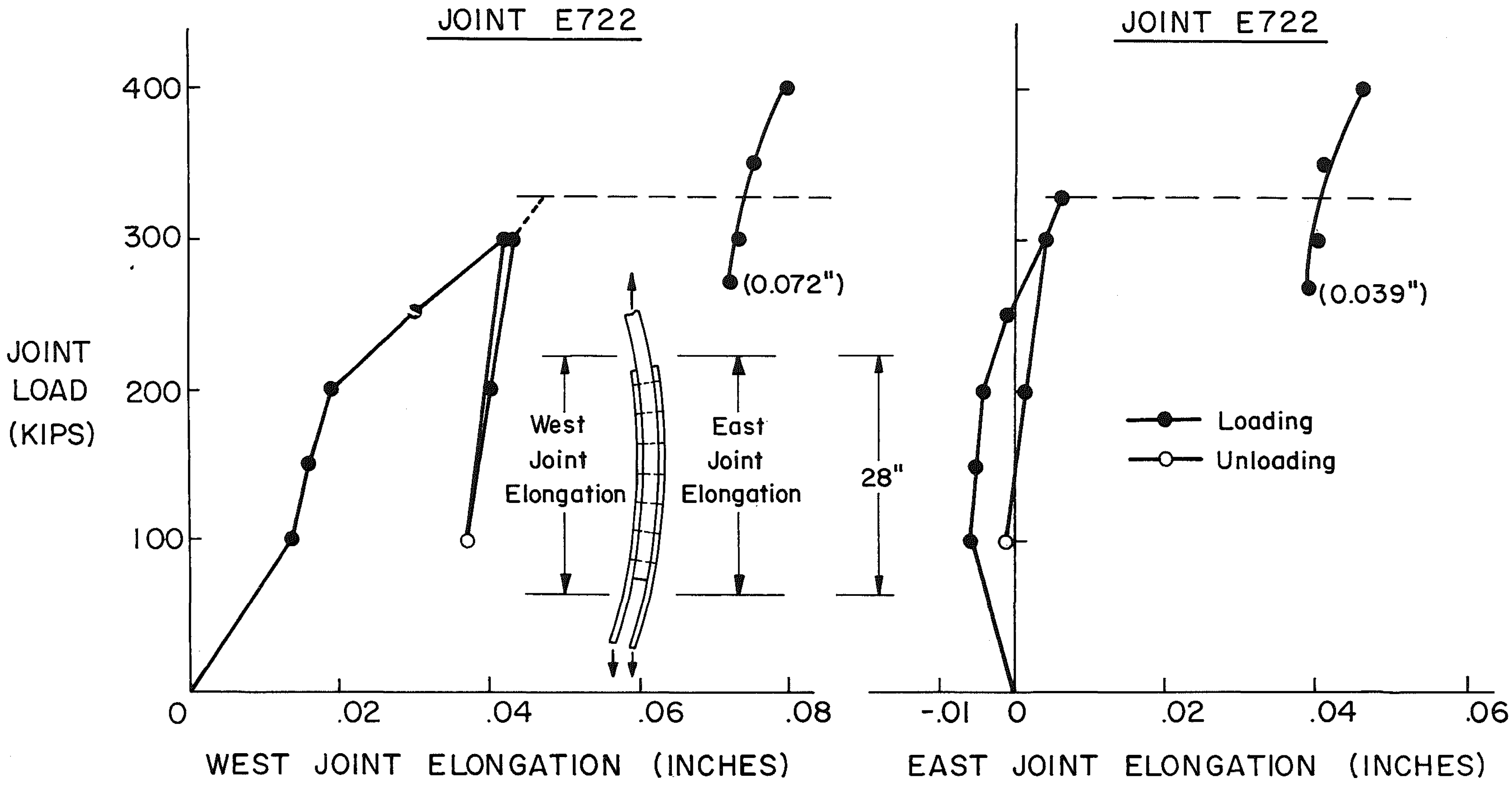


Figure 5. Curvature of Joint E722

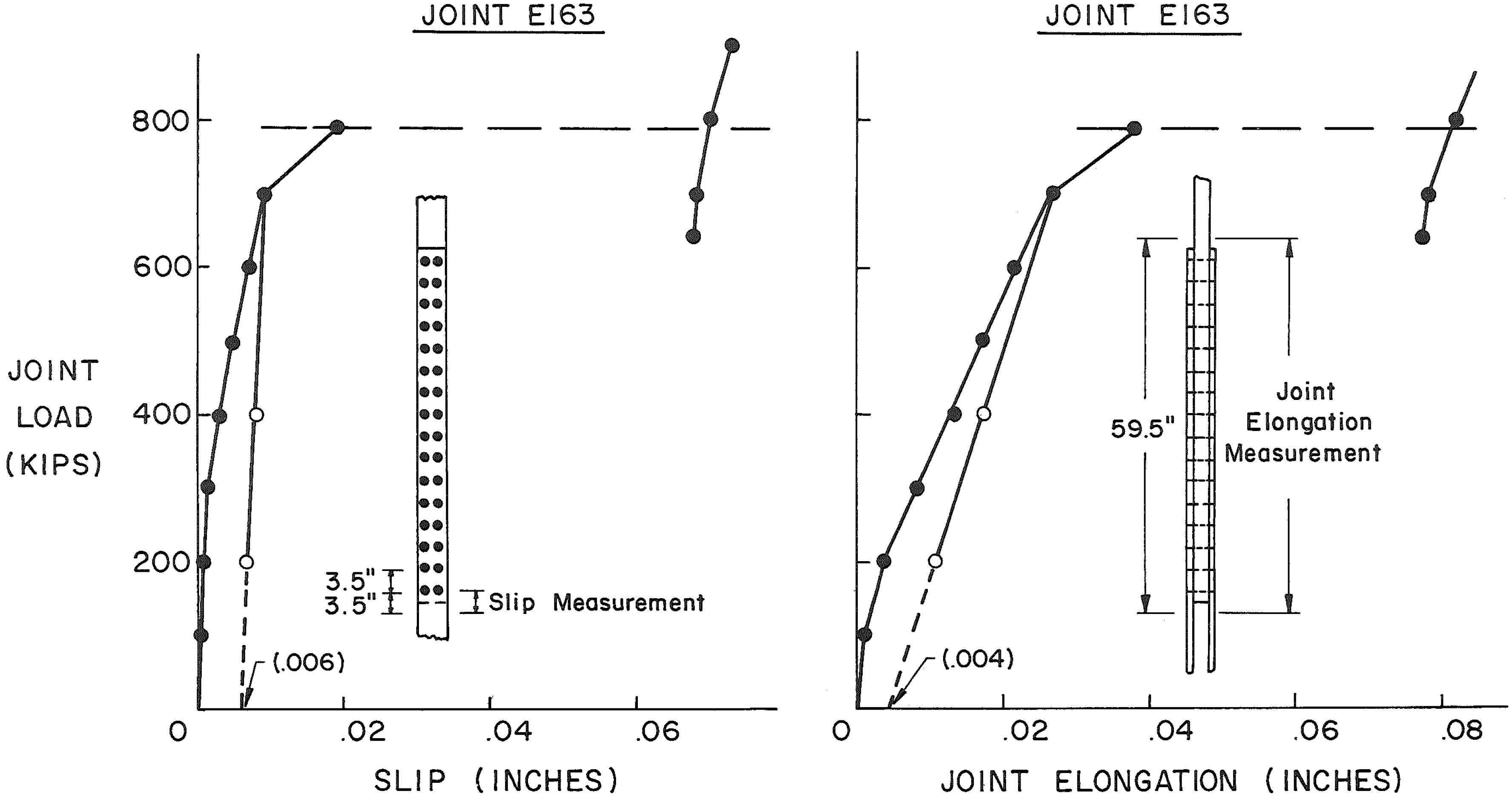


Figure 6. Pre-Slip Behavior of Joint E163

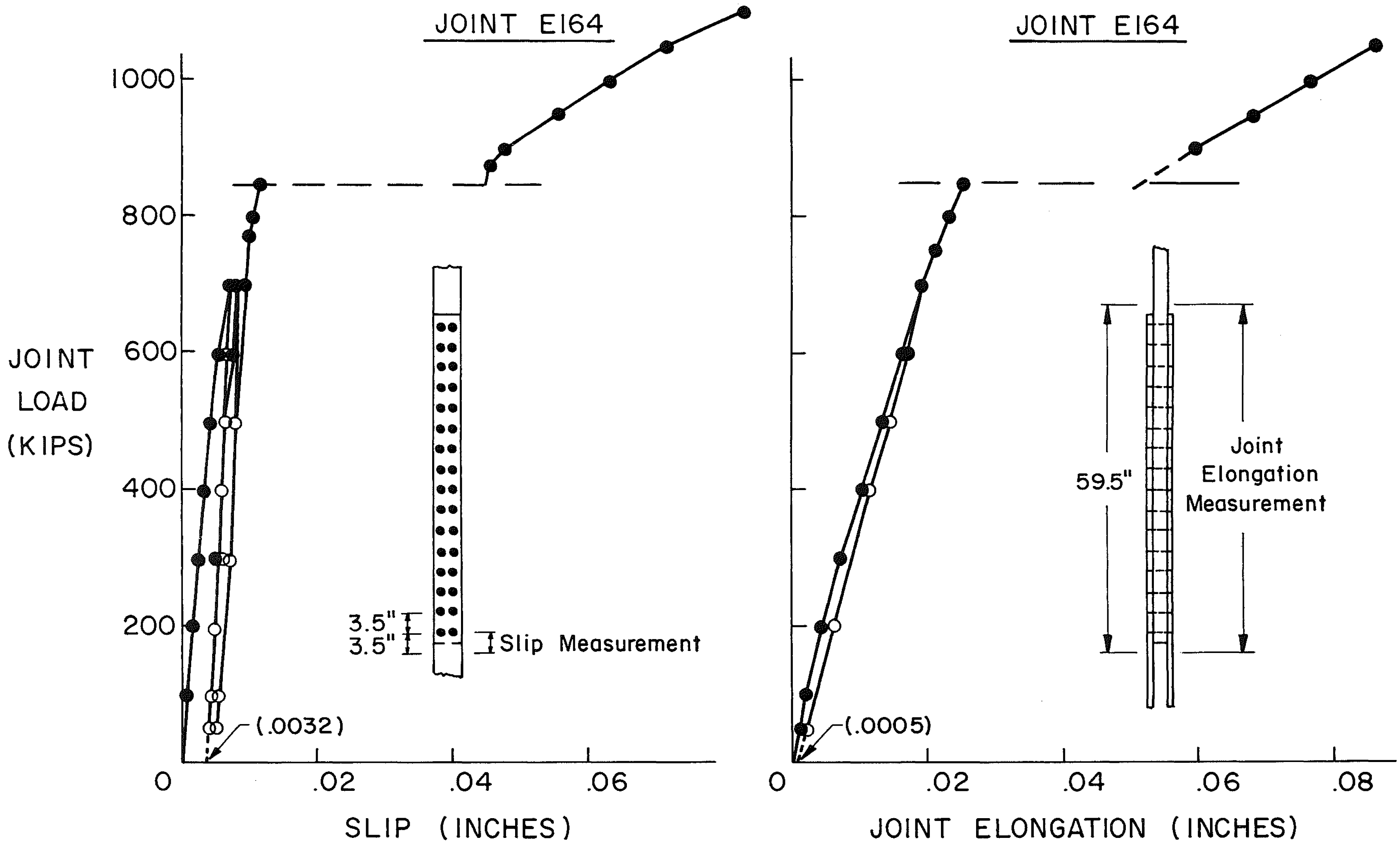


Figure 7. Pre-Slip Behavior of Joint E164

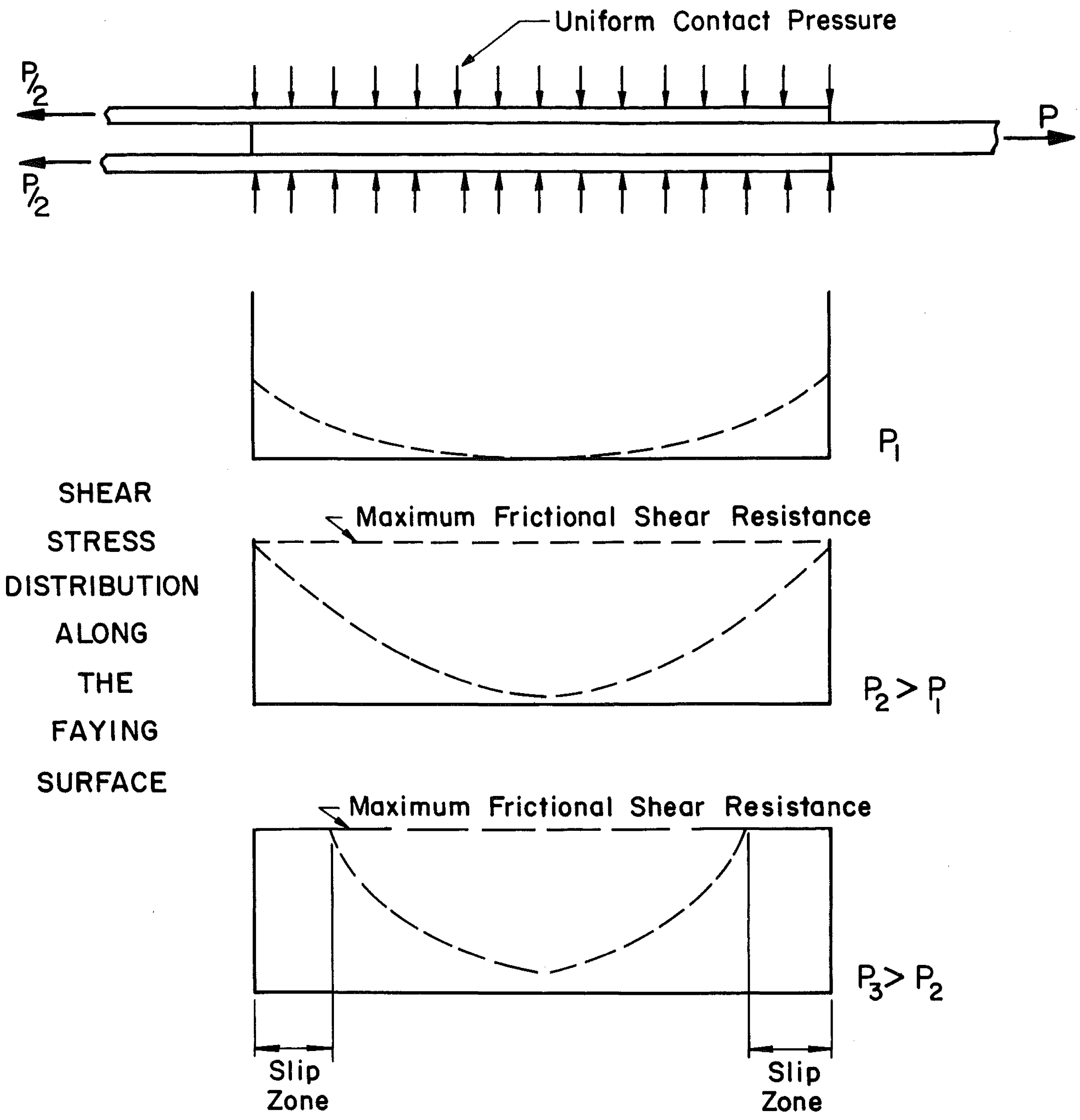
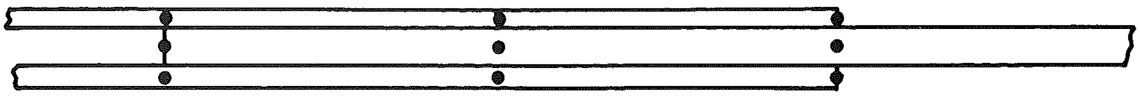
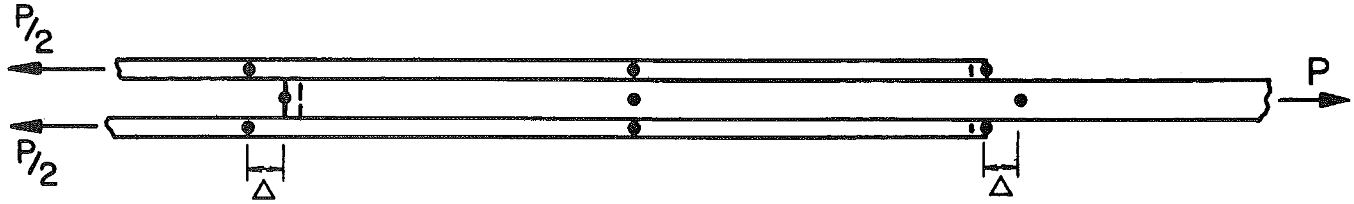


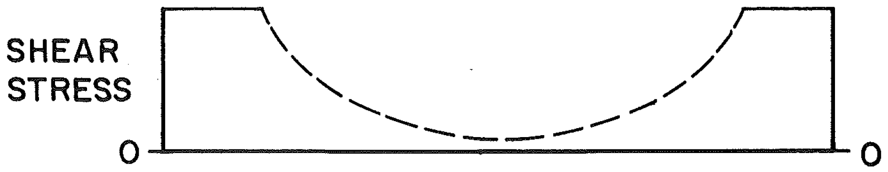
Figure 8. Shear Stress on Faying Surfaces



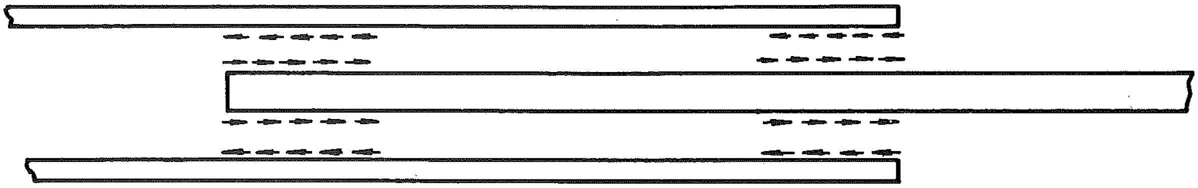
9a: Joint Under Zero Load



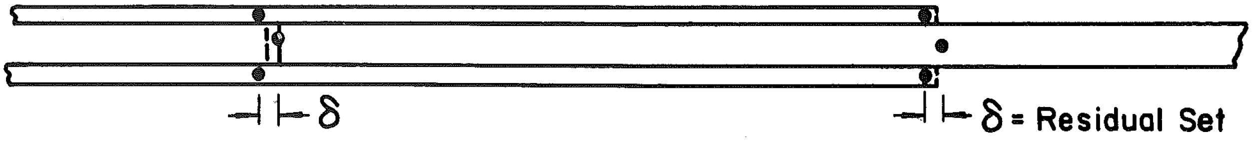
9b: Joint Under Load P



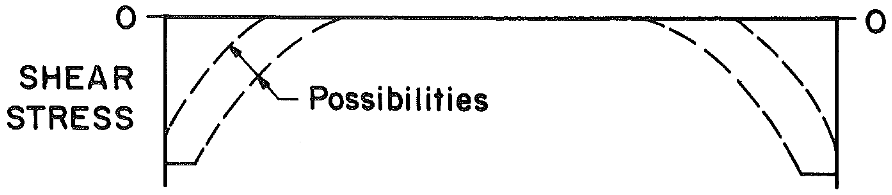
9c: Shear Stresses on Faying Surface Under Load P



9d: Local Stresses Created as Loading is Decreased



9e: Joint Under Zero Load-After Unloading



9f: Shear Stress on Faying Surface After Unloading to Zero

Figure 9.

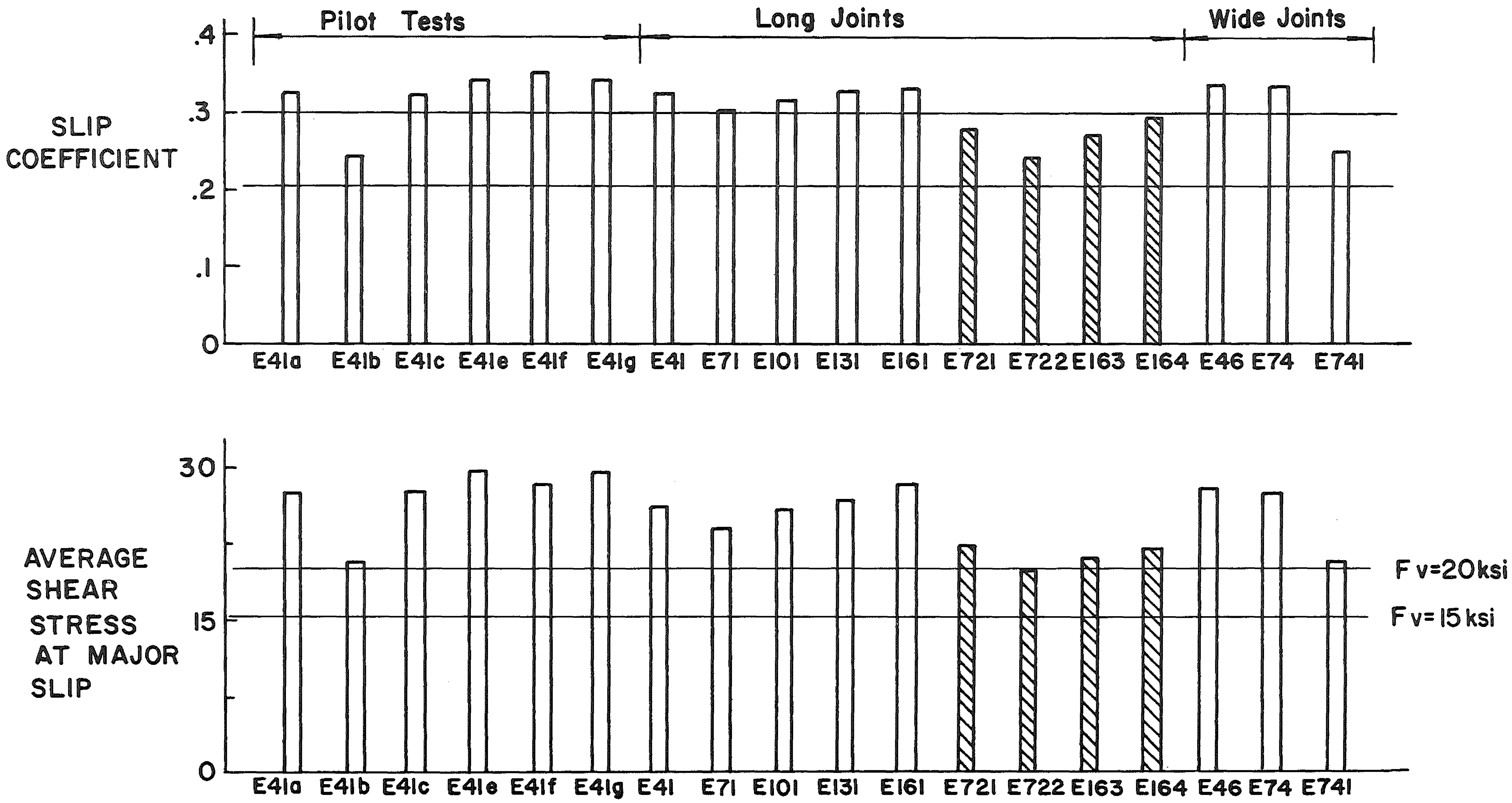
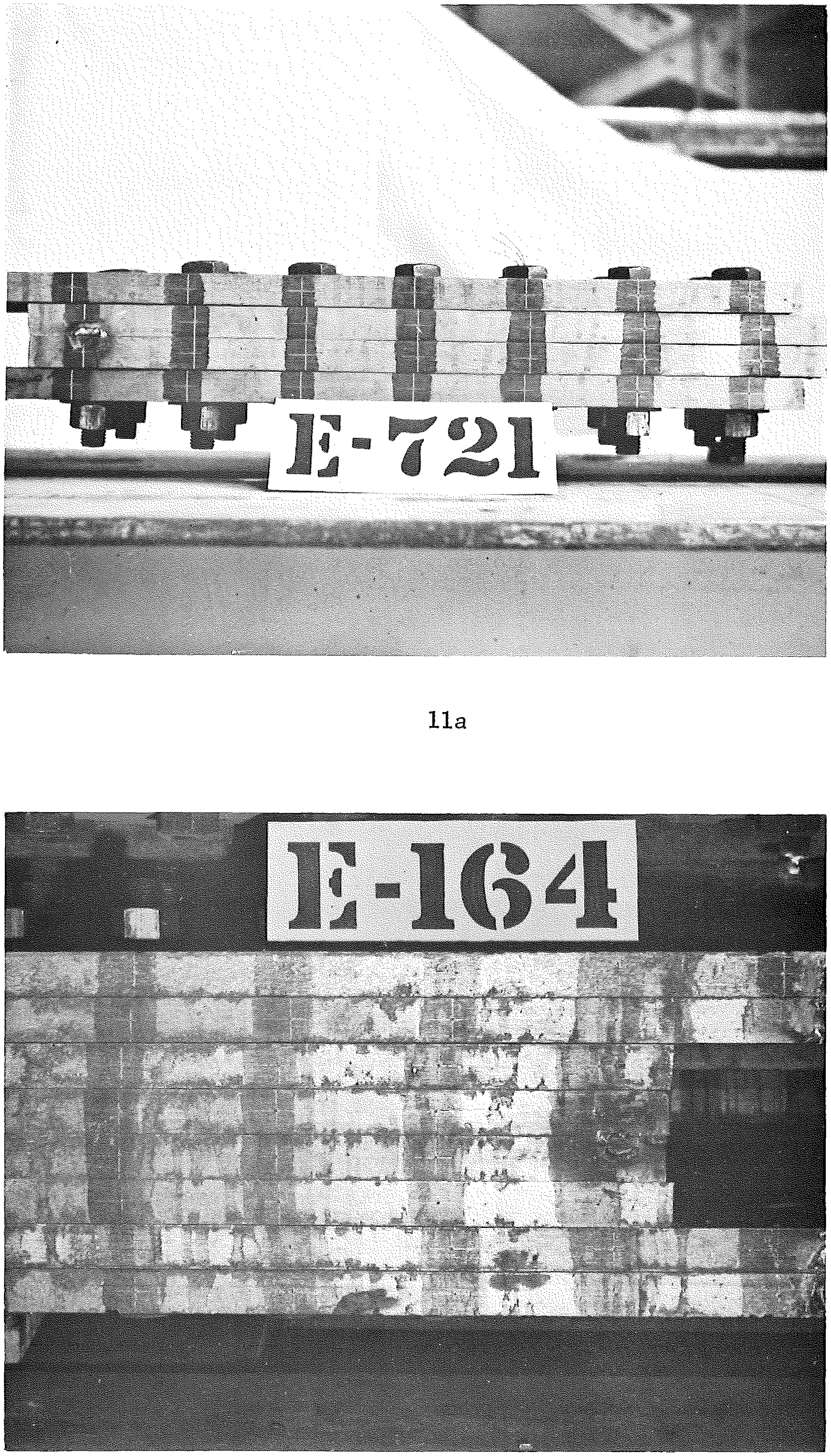


Figure 10. Slip Resistance of Bolted Joints



11a

11b

Figure 11. Shearing and Bending of Bolts.

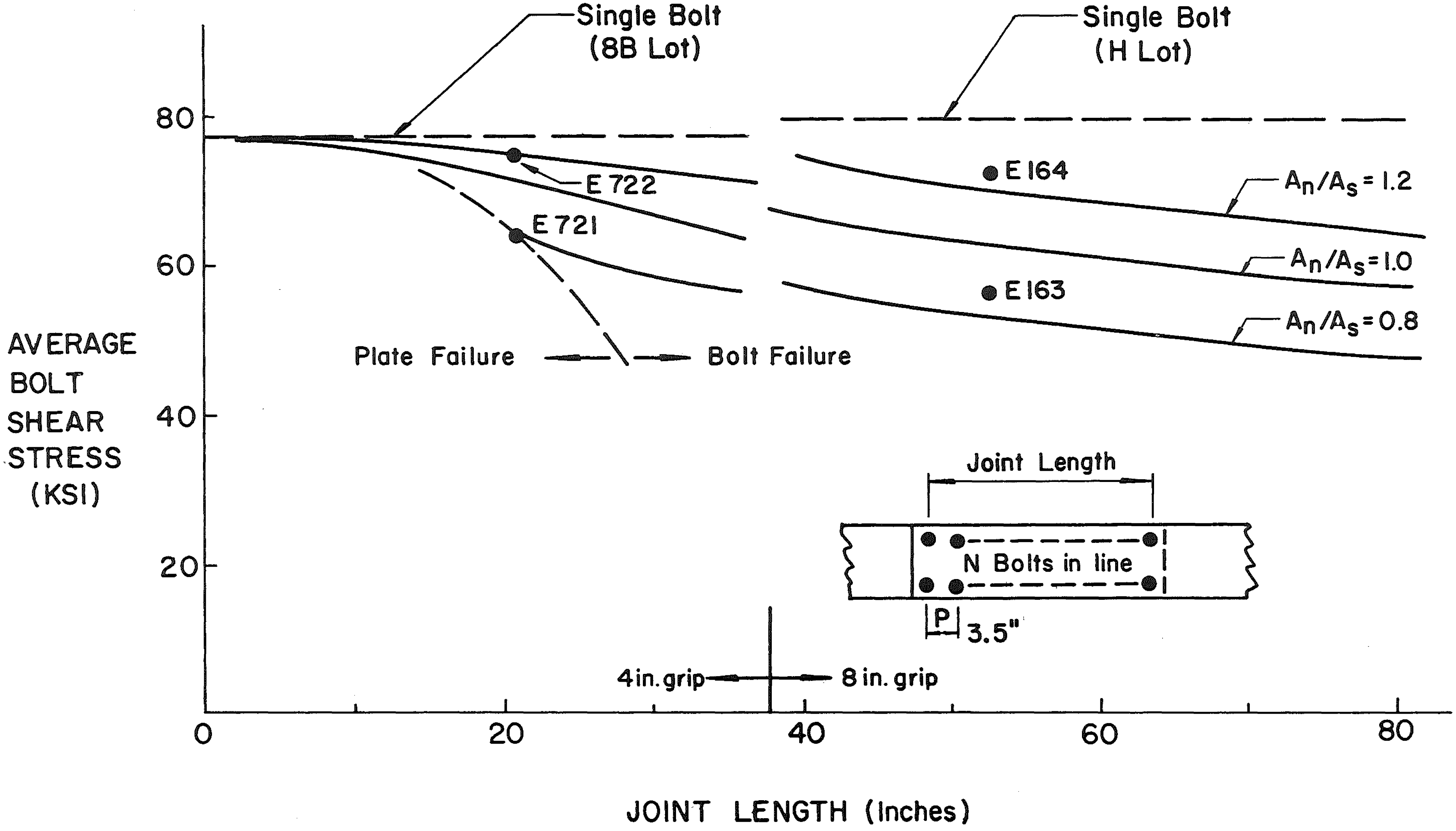


Figure 12. Test Results of Joints E721, E722, E163, and E164

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TESTS OF LONG A440 STEEL BOLTED BUTT JOINTS, Fritz Engineering Laboratory Report No. 288.26, Lehigh University, Bethlehem, Pa., February 1965.

Tests of four long structural joints fabricated from A440 steel and 7/8 in. diameter A325 bolts were conducted to determine their slip resistance and ultimate strength. The major test variables were joint length and the relative proportions of the net tensile area and the bolt shear area. Two of the joints had two lines of bolts with seven bolts per line. The remaining two specimens had two lines of bolts with sixteen bolts per line. The pitch length for all four joints was three and one half inches, or four bolt diameters. One joint of each length had the net tensile area equal to eighty percent of the bolt shear area. The other two joints had the net tensile area equal to one hundred and twenty percent of the bolt shear area. These tests have shown that some differential movement should occur between the lap and main plate at the ends of a joint prior to major slip. Major slip occurred when the frictional resistance was exceeded along the entire faying surface, and a sudden large movement was noted which caused the bolts to come into bearing. The ultimate strength of the joint was predicted with a high degree of accuracy by considering the non-linear behavior of the component parts.

KEY WORDS: bolts; joints; friction; steel; structural engineering; tensile strength; testing.

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This report describes an experimental study of the changes in bolt tension in high-strength A325 and A490 bolts connecting A440 and constructional alloy steel joints. Various bolts in seven large joints were instrumented and changes in their internal tension measured. Until major slip occurred the bolts lost only a small amount of their initial tension. This loss was due to the lateral plate contraction caused by the Poisson effect. As inelastic deformations in the plate and bolts began to occur the bolts at the lap plate end began to show an increase in tension. This was caused by the outward prying action of the plate and the resulting force was not indicative of the normal force acting on the faying surface. These tests showed that negligible load was transferred by frictional resistance near the ultimate joint strength. Also it was found that the bolts at the lap plate ends, being under a higher combined shear and tension loading than the bolts at the main plate end, were usually the first to fail.

KEY WORDS: bolts; joints; friction; instrumentation; prying; shear; steel; strength; structural engineering; testing.