1967

# Summary report to the research council on riveted and bolted structural joints, April 1967

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# STUDIES OF BOLTED CONNECTIONS

SUMMARY REPORT TO
THE RESEARCH COUNCIL ON
RIVETED AND BOLTED
STRUCTURAL JOINTS

by

Project Staff

(Not for publication)

This work has been carried out as part of the studies on Bolted Connections sponsored financially by the Pennsylvania Department of Highways, the Louisiana 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. Technical guidance is is provided by the Research Council on Riveted and Bolted Structural Joints.

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April, 1967

Fritz Engineering Laboratory Report No. 317.7

STATUS OF VARIOUS PHASES OF PROJECT 317
"BOLTED HIGH-STRENGTH STEEL JOINTS"

Sponsored by Pennsylvania Department of Highways at Lehigh University

| Phase and Topic | Remarks | Tests Performed | Tests to Be Completed | Analytical Work | Reports |
|---|---|---|---|---|---|
| I. Quenched & Tempered Steel (ASTM A514) Joints Fastened With A490 Bolts | Authorization: Committee 10 Minutes 10/1/65 Active | Pilot Studies - Six Tests. Full size tests 8 large joints. | None | Ultimate strength, load distribution, slip bebavior | In prep. |
| II. Hybrid Connections Two or more different grades of steel are joined | Authorization: Committee 10 Minutes Active | 12 shear jig tests of A36-A514 steels with A325 and A490 bolts, and A36-A440 steels with A325 bolts | 5 joints to be tested | Ultimate strength and load distribution studies | 317.3<br>317.5 |
| III. Quenched and Tempered Steel Joints Fastened With A325 Bolts | Authorization Committee 10 Minutes Active | Tension shear jigs tested, Pilot Tests J42a, J42b, J42c, J42d | 4 joints to be tested | Ultimate strength and load distribution studies | In prep. |

# PROJECT 317

Phases Now Active

| | |
|---|---|
| Phase I | Analysis and confirming static tests of quenched and tempered steel (ASTM A514) joints fastened with A490 bolts. |
| Phase II | Analysis and confirming static tests of connections in which two or more different grades of steel are joined (hybrid connections). |
| Phase III | Analysis and confirming static tests of quenched and tempered steel joints fastened with A325 bolts. |

# PROJECT 317

Summary of Reports - to December 1966

Fritz Lab Report

317.1 Project Staff
"Summary Report to Committees 10 and 23"
September, 1965

317.2 Project Staff
"Summary Report to the Research Council on Riveted and Structural Joints"
March, 1966

317.3 R. Kormanik
"The Behavior of Hybrid Bolted Connections"
Master of Science Thesis, July, 1966

317.4 Project Staff
"Summary Report to the Research Council on Riveted and Structural Joints"
July, 1966

317.5 R. Kormanik and J. W. Fisher
"Bolted Hybrid Joints"
September, 1966

317.6 Project Staff
"Summary Report to Committees 10 and 23"
December, 1966

# PROJECT 317 - PHASE I

# A514 STEEL JOINTS FASTENED BY A490 BOLTS

## 1. Introduction

An extensive theoretical and experimental investigation into the behavior of constructional alloy steel joints fastened by high strength bolts has been carried out under this phase of Project 317. A review of the experimental program and some of the conclusions reached as a result of the theoretical study are given in this report.

## 2. Description of Test Specimens

### 2.1 Pilot Tests

Ten compact joints of A514 steel fastened by high strength bolts were examined. All were four-bolt-in-line specimens in which a total thickness of 4 in. of plate was gripped by the fasteners. The geometry of these joints is shown in Fig. 1. Four of the ten joints used 1 in. diameter A325 bolts. (Although the latter are not within the scope of this Phase, they will be reported herein so that their slip behavior can be compared to the A514/A490 joints). All plate in these joints came from the same rolling and all fasteners of a given size and type came from the same lot of bolts. The test program examined both the slip behavior and ultimate strength characteristics of these joints. Complete details and test results of the pilot joints are shown in Table 1.

## 2.2 Large Joints

Although a considerable number of tests have been performed in the past on large, bolted plate splices, these were all made on joints of structural carbon (A7 and A36) or high strength (A440) steels.[1] It has been shown that joints of constructional alloy steel behave in a significantly different manner from those grades previously investigated.[2] To verify these theoretical predictions, it was felt that an extensive experimental investigation using full size joints was required. Although the pilot tests did provide valuable information, particularly with regard to the slip behavior of A514 steel joints, it has been shown that one of the most important variables affecting joint behavior is joint length.[3] Thus, the test program involving large joints was developed.

The large joint test series consisted of eight specimens. All used A490 bolts, of various grips, to fasten A514 steel plates. Seven of these specimens used 7/8 in. diameter fasteners and one used 1-1/8 in. diameter fasteners. All plate in these joints came from the same rolling. The geometry of the joints is shown schematically in Fig. 1 and complete details and test results are shown in Table 2.

Two joints each of seven, 13, 17, and 25 fasteners in line were tested. The first six specimens were paired, one of each pair designed to fail by tearing of the plates, the other by shearing of the fasteners. The mode of failure is governed by the relative proportions of the plate and fasteners. This can be described by means of the $A_n/A_s$ ratio, where $A_n$ is the net area of either the main or lap plates and $A_s$ is the total associated shear area of the fasteners. These six joints, then, bracket the plate failure - fastener failure boundary line.

The remaining two specimens, those of 25 bolts in line, were both designed to fail in the fasteners. The analytical studies have pointed out that it is not until constructional alloy steel joints reach about this length that any substantial amount of load inequality occurs among the fasteners. Since it was necessary that the mathematical models developed[2] for determining this effect be verified, these long joints were chosen.

## 3. Analytical Studies of Ultimate Strength

### 3.1 Basis of the Examination

In examining the application of the theory that has been developed for determining the ultimate strength of constructional alloy steel joints fastened by high strength bolts,[2] it is appropriate to base the approach on the use of plate and fasteners of minimum strength. A lower bound to the behavior of such joints will result.

### 3.2 Location of the Plate Failure - Fastener Failure Boundary

The first step in the determination of the ultimate strength of a bolted joint must be to establish the mode of failure. The location of the boundary between plate failure and fastener failure is most conveniently found by a converging process. At a given joint length, the ultimate strengths of joints with decreasing values of $A_n/A_s$ are computed. The process must start in the fastener failure region, that is, at a value of $A_n/A_s$ high enough to ensure this failure mode. With each calculation, the ultimate load so computed is compared to the ultimate load of the plates, as represented by $A_n \cdot \sigma_u$ at that step. If these two loads are equal, or within an acceptable limit, a point on the boundary has been obtained. This process is repeated for other joint lengths until the complete curve has been obtained for the desired range.

The plate failure - fastener failure boundary shown in Fig. 2 has been computed on the basis of 7/8 in. diameter A490 bolts of minimum strength connecting a total of four inches of minimum strength A514 plate. The fastener pitch was taken as 3.5 inches. The effects of different grips, pitches, and fastener diameter will be examined but are not discussed further in this report. Their influence on the location of the boundary or on ultimate joint strength is expected to be minor.

The dashed horizontal line extending across the graph in Fig. 2 at a shear stress value of 91.5 ksi represents the "ideal" joint, that is, one in which all the fasteners carry an equal load. This occurs, of course, only at a value of $A_n/A_s = \infty$. Shown between this limiting line and the other limit, the plate failure boundary, are joint strength curves for $A_n/A_s$ values of 1.00, 0.80, 0.70, and 0.60.

Two important facts are observable from these curves. First, when A514 steel is connected by A490 bolts, it is unlikely that joint proportions will be such that failure will occur in the fasteners. For example, using an allowable stress value of 60 ksi for A514 plate in combination with the allowable stress value for A490 bolts used in buildings, an $A_n/A_s$ ratio of 0.53 results. As shown in Fig. 3 where the same boundary is plotted as $A_n/A_s$ vs. joint length, at these stress levels the joint would have to be longer than about 84 in. before the fasteners would be critical. Recently, an allowable stress of 40 ksi has been suggested for A490 bolts used in bearing connections.[4] The $A_n/A_s$ value in this case would be 0.67. Examining Fig. 3 again, it can be seen that plate failure would now be the governing failure mode up to a joint length of 60 in.

The second observation that can be made from Fig. 2 concerns the effect of the spacing of the fastener failure curves shown. For example, at a joint length of 70 in., the limiting $A_n/A_s$ curves of 0.62 and $\infty$ cover a range of shear stress values of only 75.8 ksi to 91.5 ksi. This means that the load carried by a joint with $A_n/A_s = 0.62$ will not be greatly less than a joint at the same length with, say, $A_n/A_s = 1.00$. The theoretical values of load for one line of bolts for this illustration would be 1915 kips and 2258 kips, respectively. In other words, although the plate area was increased 61%, the load that could be carried increased only 18%. The effect of adding more plate area in order to make the fasteners work at higher stress level does not seem particularly advantageous.

### 3.3 Behavior of Fastener Failure Joints

In specimens in which joint proportions are such that fastener failure is expected, the load level among the bolts will be fairly uniform. The very high yield level of A514 steel means that inelastic deformation will occur to some extent in all bolts while the plate material is still elastic and relatively rigid. As an example, referring again to the behavior of minimum strength 7/8 in. diameter A490 bolts in minimum strength A514 plate, the average shear stress in the fasteners of a 17-bolt joint ($A_n/A_s = 0.80$) at time of failure is only about 8% less than the maximum shear stress in a single bolt.

## 4. Test Results and Analysis

### 4.1 Load - Deformation Behavior

Complete load - deformation data were taken for each joint described in Section 2. Typical results are shown for a long joint in Fig. 4 where the behavior of Specimen J171 is illustrated. The load - deformation response is nearly linear up to the point of major slip. At this load, which was a well-defined point in all of the tests except one, the main and lap plates moved relative to one another a little less than the amount of the hole clearance. This movement was always sudden and was accompanied by a sharp "bang" as some or all of the fasteners came into bearing.

Following major slip, the load - deformation response was again linear for a short time until a second, minor slip took place. Inelastic deformations in both plate and bolts then began to occur. For those specimens failing by fracture of the plates, such as the one illustrated in Fig. 4, the curve became very flat as the eventual failure load was approached. Specimens designed to fail by fastener shear approached the failure load on a much steeper slope because of their relatively greater plate area.

The exception to this general behavior among the large joints was Specimen J251. Here, slip occurred in three almost equal increments at greatly different loads. After bolting up, this specimen had a large initial curvature and a horizontal jack had to be used to force the joint into the grips of the testing machine. Because of this behavior, the data from this test was not used in analyzing the slip behavior of these joints.

The pilot joints behaved in a very similar fashion to that described here. However, none showed the second, minor slip that was observed in most of the large joint tests.

## 4.2 Slip Behavior

The slip behavior of bolted joints has customarily[1] been examined on the basis of a "slip coefficient" ($K_s$). This is defined as

$$K_s = \frac{P_s}{m \ n \ T_i}$$

where $P_s$ is the slip load, m is the member of faying surfaces, n is the number of bolts, and $T_i$ is the average clamping force per bolt. Slip coefficients computed on this basis are shown in Tables 1 and 2 for the pilot and large joint tests, respectively.

Variations in the value of the slip coefficient appear to be random, that is, they are independent of joint length or width, or magnitude of clamping force. For example, Specimens J131 and 132, which have the same joint length and differ only slightly in width, have identical values of $K_s$ in spite of a large difference in clamping force. Specimens J172 and F42e have approximately the same clamping force per bolt but lengths of 56 in. and 10-1/2 in., respectively. The values of $K_s$ for these two joints also are identical.

The mean value of $K_s$ for the seventeen joints included in the study is 0.33 with a standard deviation of 0.04. The results are shown graphically in Fig. 5. It should be pointed out that all of the plate used in these tests was blast-cleaned with chilled steel grit. Although this is not an unusual shop procedure for alloy steel plate, it probably results in a slip coefficient that is on the conservative side.

The average shear stresses at time of major slip and depending upon fastener type are shown in Fig. 6. Also shown are the working stress levels for the two types of bolts when used in buildings, according to currently used specifications.[5] Based on mean values, the factors of safety against slip are 1.48 and 1.86 for A325 and

A490 bolts, respectively. The recommended values for structures designed according to AISC Specifications are 1.40 for A325 bolts and 1.44 for A490 bolts.

### 4.3 Ultimate Load Behavior

#### a. Pilot Tests

The four pilot joints fastened by A490 bolts were all expected to fail by shearing of the fasteners. The theoretical studies showed that almost no inequality of load would occur among the fasteners in joints of this short length. Hence, predicted ultimate loads were taken simply as multiples of the individual fastener strengths. The maximum error on predictions so computed was only 2.3%. All predicted and actual ultimate loads are shown in Table 1.

#### b. Large Joints

The use of a plate - with - holes coupon to predict the ultimate load of the plate failure specimens gave values virtually identical to the actual loads. All joints failed in the mode predicted and failure was always through an end bolt hole, either in the main plates or in the lap plates.

The analytical method which has been developed to predict the ultimate load of A514 steel joints failing by fasteners shear also gave excellent results.[2] The maximum error in ultimate load predictions of the five large joints tested was 5.3%. All test results are shown in Table 2.

## 5. Philosophy of Design of Constructional Alloy Steel Members

### 5.1 Review of Current Design Philosophy

The design of structural steel tension members and the design of their connections must be carried out in accordance with an inter-related philosophy. The philosophy that has been established for the design of the member considers that the limit of usefulness is given by the load at which contained plastic flow commences in the gross section of the member.[6,7] Beyond this point, "significant and relatively uncontrolled" elongation occurs.[6]

The philosophy of design of bolted connections in tension members of carbon and high strength structural steels has recently been examined.[4] In order to fulfill the requirements set forth for the member itself, this reference points out the need for joint proportions that will produce yielding in the gross section of the member before the joint fails. This joint failure can be either by tearing of the plates through the net section or by fastener shear. The criteria proposed by these researchers ensures this action.

Although allowable stresses have not yet been established for tension members of constructional alloy steel, it seems clear that the same philosophy of design will be used. This means that bolted joints within A514 steel members will also have to ensure that yield is reached or exceeded in the gross section of the member before the joint fails.

## 5.2 Characteristics of A514 Steel Members Designed According to Current Practice

It was shown in Art. 3.2 that constructional alloy steel joints using A490 bolts proportioned to suggested allowable plate stresses and current allowable fastener stresses will be governed by the plate failure mode over a large range of joint length. Even at the higher allowable bolt stress level of 40 ksi, plate failure is the governing mode for joints up to about 60 in. long.

As outlined in Art. 5.1, it is considered desirable that tension members yield across their gross cross-section before they fail, either through the net cross-section or in the fasteners. For plate failure type joints, and using minimum specified yield and ultimate stresses for A514 steel, this means that the net area of the member ($A_n$) should be equal to or greater than 87% of the gross area ($A_g$).

If a simplified type of member, one composed of plate elements of constant thickness containing non-staggered lines of fasteners in drilled holes is considered, an indication of the effect of the $A_n/A_g$ requirement can be obtained. It has been shown that the minimum allowable spacing of fasteners, measured perpendicular to the line of the load, is about seven times the bolt diameter.[8] It is doubtful whether such a large minimum spacing can be accepted in structural practice. Although there is evidence to support it,[2] there is also some question as to whether an A514 member can attain a joint efficiency of 0.87 or greater.

Examination of the other class of joint, those whose factor of safety is against failure of the fasteners, shows that plate stresses in the gross section of the member will be above yield at the time of joint failure. The factor of safety against shear failure in the bolts is also at a satisfactory level.

## 5.3 Proposed Design Criteria for Bolted Joints in A514 Steel Members

To this point, examination of the behavior of A514 members using A490 bolts has shown that:

1. A large class of joints, those up to about 60 in. long when an allowable stress of 40 ksi is used in the fasteners, will have a plate failure type of failure mode.

2. Using normal fabrication methods, that is, forming the joint by deducting holes from the gross section of the member, it seems doubtful that plate failure type joints can be proportioned to produce satisfactory member behavior.

3. Joints over 60 in. long have a fastener shear failure mode. Both joint and member behavior are satisfactory.

Under present fabrication technique, the only way to meet the criterion desired for member behavior is to increase the allowable fastener stress and/or reduce the allowable tension stress in the plate material. This approach has been examined in detail.[2] Increasing the allowable fastener shear stress from the 40 ksi level is unsatisfactory. The factor of safety against shear failure of the fasteners is about at the minimum desirable value (1.98 at a joint length of 84 in.) at this stress level. It would also be unwise to suggest an allowable stress different than that suitable for the same type of fastener when used in other grades of steel.[4]

The use of a lower allowable stress in the plate material is likewise unsatisfactory. Although lowering the allowable stress from 60 ksi to 50 ksi produces joint proportions such that fastener failure governs for all joint lengths, it will not produce the desired yielding in the member before joint failure.

It is apparent that if the design philosophy established is to be fulfilled for constructional alloy steel tension members, some alternative to the approaches discussed above will have to be used. On the basis of the investigation reported in Reference 2, the following are suggested:

1. Some type of upset end, such as an increase in plate width over the length of the joint, could be used.

2. The specified material properties of constructional alloy steel could be changed.

The first alternative, the use of upset ends, means simply that more material would be provided in the region of the connection. This would overcome the difficulties described in meeting the net to gross member area requirement. The net section of the upset end would be established at 87% or more of the gross section of the main member. The allowable stresses could be kept at 60 ksi in the plate and at 40 ksi in the bolts. The use of upset ends would then be required for joints up to 60 in. long. Joints greater than this length could be fabricated in the normal manner.

The other approach to the problem of providing satisfactory member behavior is to change the specified material properties of constructional alloy steel. The principal reason for the unsatisfactory behavior of plate failure type joints and their members is the low spread between the yield and ultimate stress of A514 steel. The situation would be considerably improved if the minimum specified ultimate stress were increased from the present level of 115 ksi to, say, 125 ksi while the minimum specified yield stress is kept at 100 ksi.

This change would reduce the $A_n/A_g$ requirement from 0.87 to 0.80. Assuming the same allowable stress levels in the plate (60 ksi) and in the bolts (40 ksi), the proportion of plate failure type joints could be expected to remain about the same. However, fabrication of these joints, those under about five feet in length, could probably be done in the normal manner. The joint could be prepared by drilling holes in the section provided by the main member as long as the area provided in the net section is kept at a minimum of 80% of that of the gross section. The minimum allowable fastener spacing would now be about 4-1/4 times the fastener diameter.

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## TABLE 1

JOINT DIMENSIONS AND TEST RESULTS - PILOT STUDY

| Item | Units | F42a | F42b | F42c | F42d | F42e | F42g | J42a | J42b | J42c | J42d |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bolts Type | - | A325 | A325 | A325 | A325 | A325 | A325 | A490 | A490 | A490 | A490 |
| Diameter | in. | 1-1/8 | 1-1/8 | 1-1/8 | 1-1/8 | 1-1/8 | 1-1/8 | 1 | 1 | 1 | 1 |
| No. in Line (n)* | - | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Shear Area ($A_s$) | $in.^2$ | 15.90 | 15.90 | 15.90 | 15.90 | 15.90 | 15.90 | 12.57 | 12.57 | 12.57 | 12.57 |
| Joint Length | in. | 10.5 | 10.5 | 10.5 | 10.5 | 10.5 | 10.5 | 10.5 | 10.5 | 10.5 | 10.5 |
| Plate Width | in. | 5.56 | 6.36 | 6.76 | 7.16 | 7.56 | 7.96 | 6.84 | 7.16 | 7.47 | 7.79 |
| Thickness (t) | in. | 2.03 | 2.04 | 2.04 | 2.04 | 2.04 | 2.05 | 2.04 | 2.05 | 2.04 | 2.05 |
| Gross Area ($A_g$) | $in.^2$ | 11.28 | 12.98 | 13.80 | 14.51 | 15.41 | 16.31 | 13.93 | 14.63 | 15.24 | 15.95 |
| Net Area ($A_n$) | $in.^2$ | 6.40 | 8.07 | 8.90 | 9.66 | 10.52 | 11.40 | 9.58 | 10.25 | 10.85 | 11.55 |
| $A_n/A_s$ | - | 0.40 | 0.51 | 0.56 | 0.61 | 0.66 | 0.72 | 0.76 | 0.82 | 0.86 | 0.92 |
| Slip Load | kips | 396 | 332 | 326 | 342 | 346 | 398 | 480 | 506 | 518 | 448 |
| Clamping force/bolt | kips | 69.0 | 70.0 | 68.5 | 70.5 | 69.0 | 70.0 | 86.0 | 80.0 | 80.0 | 80.0 |
| Slip Coefficient | - | 0.36 | 0.30 | 0.30 | 0.30 | 0.31 | 0.36 | 0.35 | 0.40 | 0.40 | 0.35 |
| Ultimate Load | | | | | | | | | | | |
| Predicted | kips | | | | | | | 1210 | 1210 | 1210 | 1210 |
| Actual | kips | | | | | | | 1238 | 1228 | 1206 | 1220 |
| Failure Mode | - | | | | | | | Bolts | Bolts | Bolts | Bolts |

* Pitch = 3.5 in. for all joints.

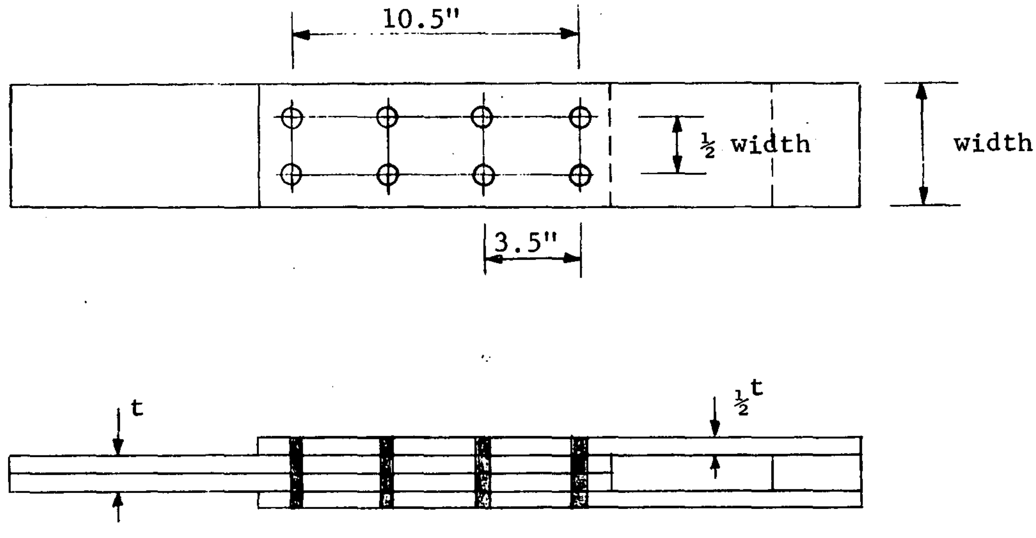
TABLE 2

JOINT DIMENSIONS AND TEST RESULTS - LARGE JOINTS

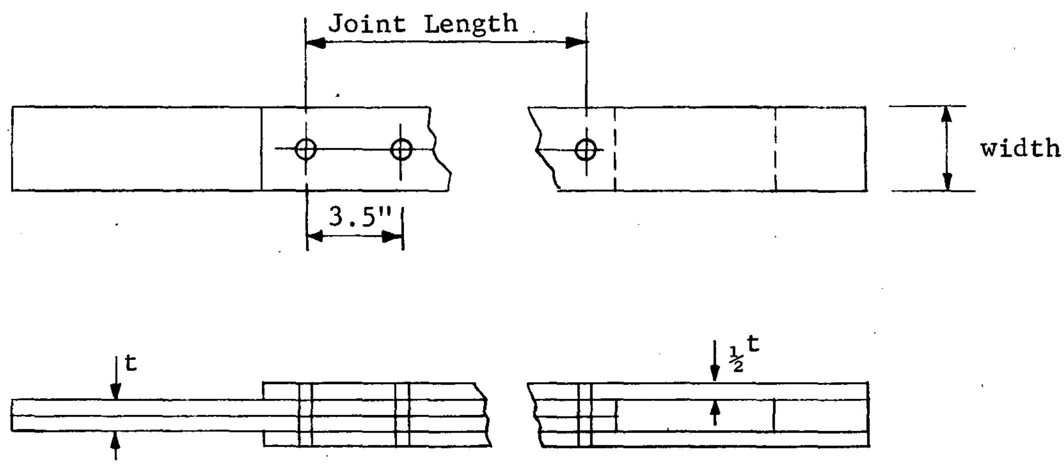
| Item | Units | J071 | J072 | J131 | J132 | J171 | J172 | J251 | J252 |
|---|---|---|---|---|---|---|---|---|---|
| <u>Bolts</u> Type | - | A490 | A490 | A490 | A490 | A490 | A490 | A490 | A490 |
| Diameter | in. | 7/8 | 7/8 | 7/8 | 1-1/8 | 7/8 | 7/8 | 7/8 | 7/8 |
| No. in Line* (n) | - | 7 | 7 | 13 | 13 | 17 | 17 | 25 | 25 |
| Shear Area ($A_s$) | in.$^2$ | 8.41 | 8.41 | 15.63 | 25.84 | 20.44 | 20.44 | 30.07 | 30.07 |
| Joint Length | in. | 21 | 21 | 42 | 42 | 56 | 56 | 84 | 84 |
| <u>Plate</u> Width | in. | 3.86 | 4.71 | 6.38 | 7.00 | 8.07 | 10.09 | 6.97 | 9.22 |
| Thickness (t) | in. | 2.03 | 2.04 | 2.04 | 4.08 | 2.04 | 2.02 | 4.08 | 4.08 |
| Gross Area ($A_g$) | in.$^2$ | 7.82 | 9.58 | 12.99 | 28.55 | 16.48 | 20.40 | 28.35 | 37.55 |
| Net Area ($A_n$) | in.$^2$ | 5.92 | 7.66 | 11.08 | 23.70 | 14.55 | 18.52 | 24.55 | 33.73 |
| $A_n/A_s$ | - | 0.70 | 0.91 | 0.71 | 0.91 | 0.71 | 0.90 | 0.82 | 1.12 |
| <u>Slip</u> Load | kips | 270 | 364 | 620 | 974 | 730 | 700 | ** | 938 |
| Clamping force/bolt | kips | 71.3 | 69.7 | 70.5 | 110.5 | 66.6 | 66.9 | 72.1 | 72.0 |
| Slip Coefficient | - | 0.27 | 0.37 | 0.34 | 0.34 | 0.32 | 0.31 | - | 0.26 |
| <u>Ultimate Load</u> | | | | | | | | | |
| Predicted | kips | 700 | 810 | 1309 | 2485 | 1720 | 1950 | 2740 | 2935 |
| Actual | kips | 710 | 850 | 1308 | 2615 | 1718 | 2015 | 2735 | 3100 |
| Failure Mode | - | Plate | Bolts | Plate | Bolts | Plate | Bolts | Bolts | Bolts |

* Pitch = 3.5 in. for all joints

** Not defined - joint was warped




Pilot Joints




Large Joints

Fig. 1 Geometry of Test Joints

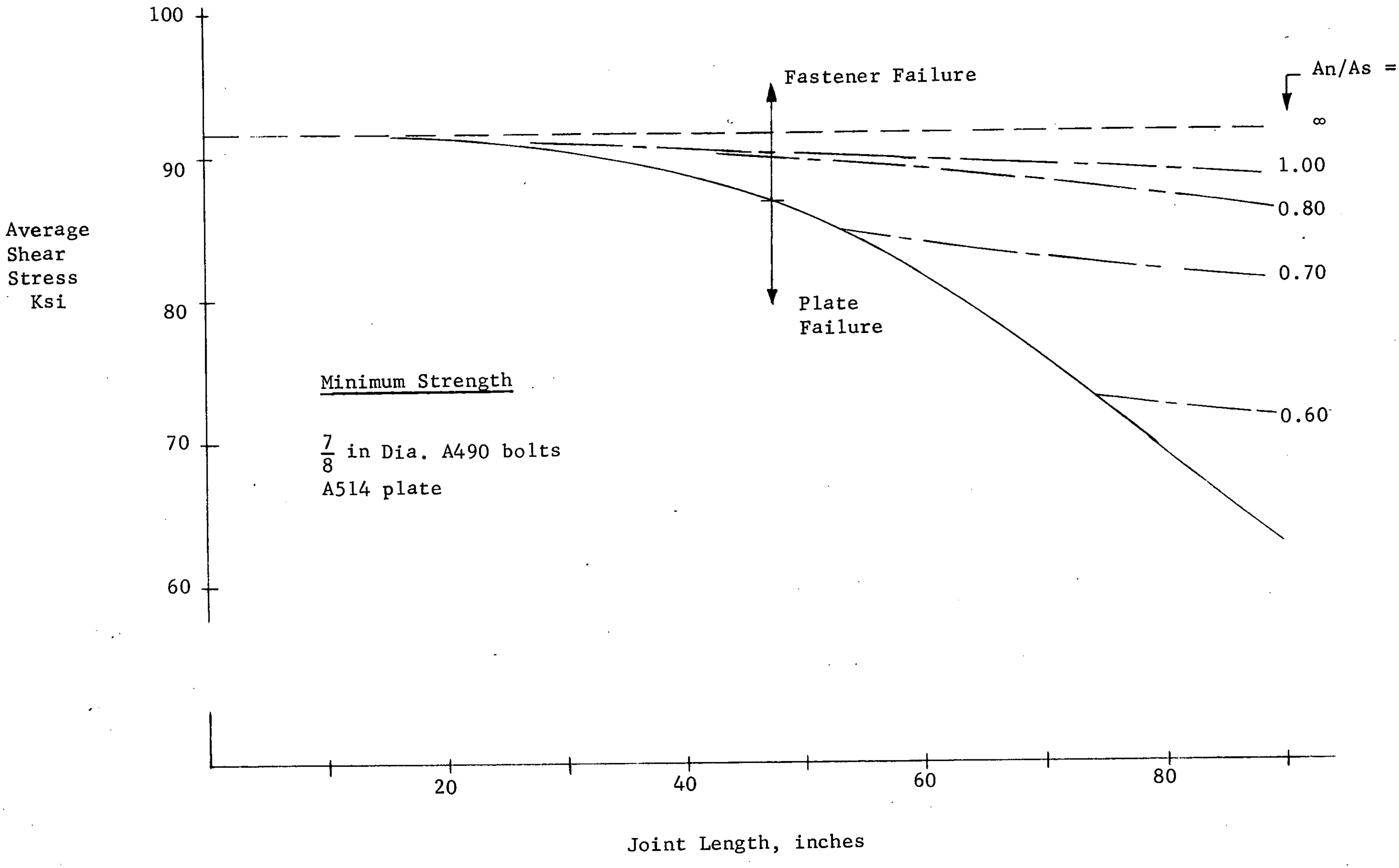



Fig. 2 Plate Failure - Fastener Failure Boundary, $\tau$ vs. L.

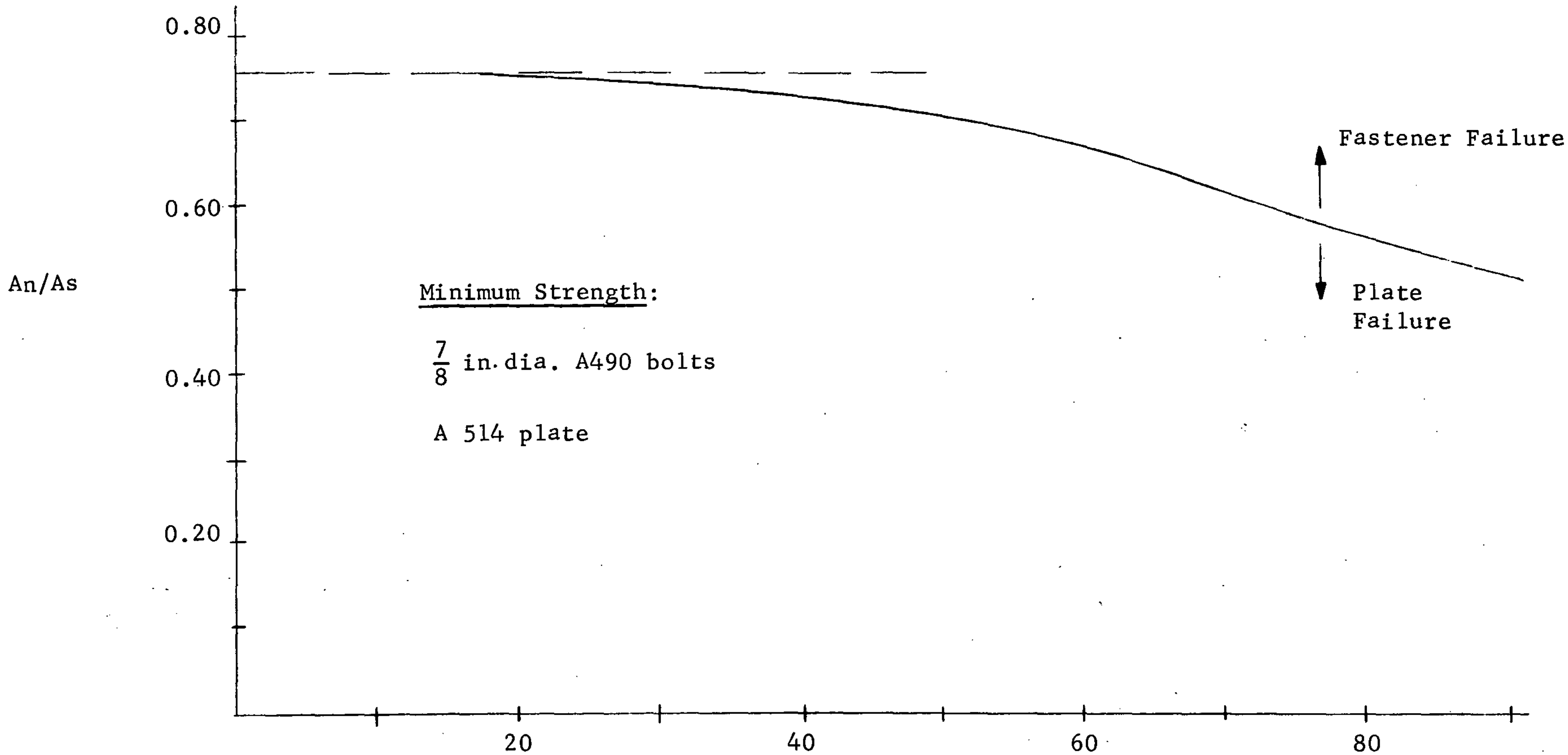



Fig. 3 Plate Failure - Fastener Failure Boundary, An/As vs. L.

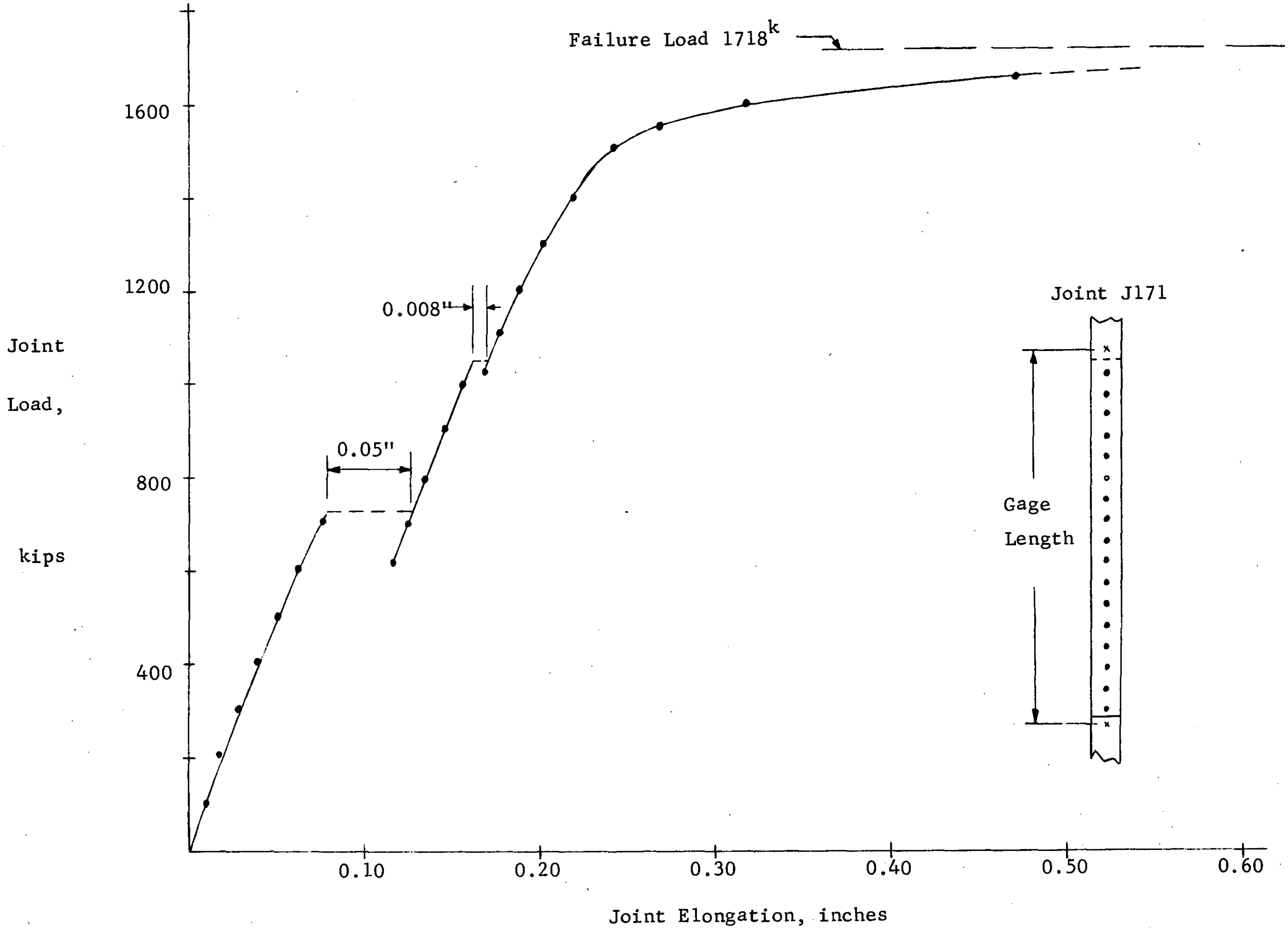



Fig. 4 Typical Load - Deformation Response

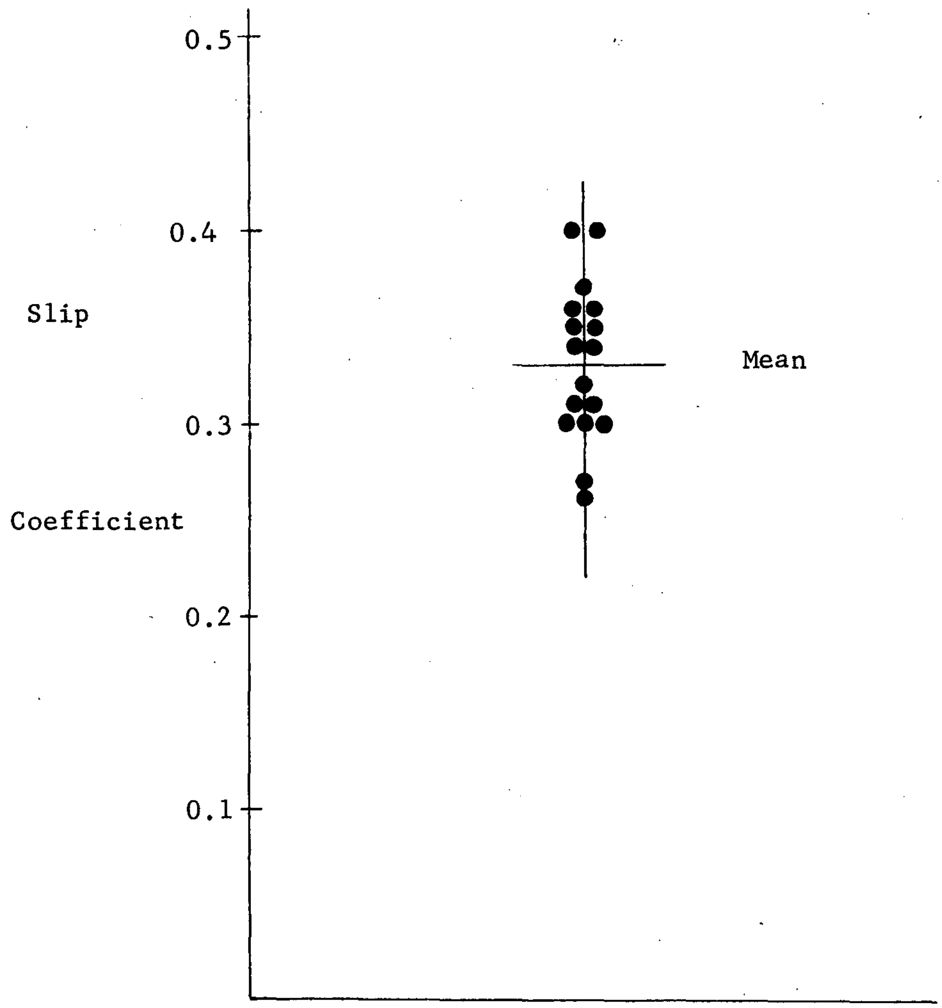



Fig. 5 Slip Coefficient

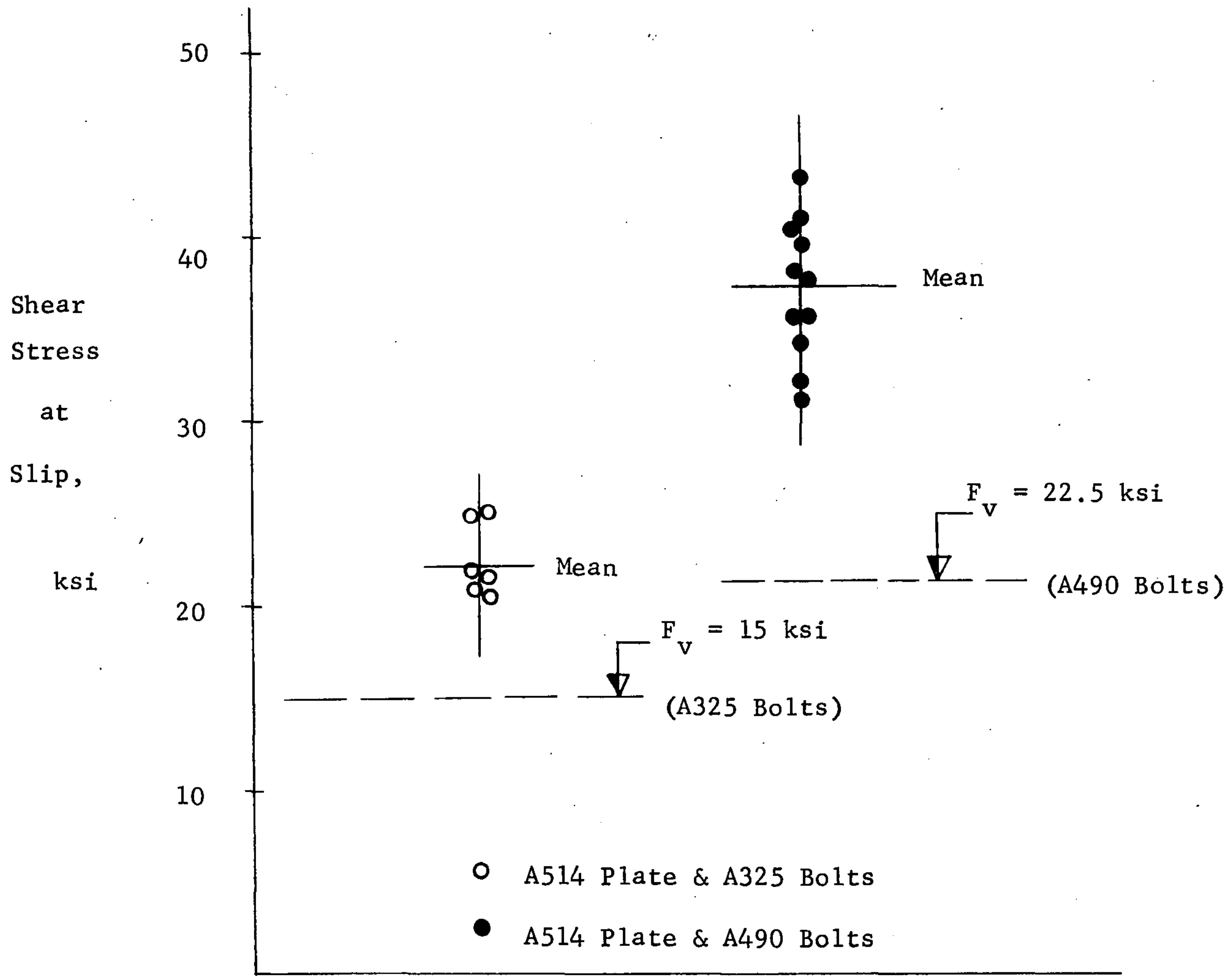



Fig. 6 Slip Resistance

STATUS OF VARIOUS PHASES OF PROJECT 318
"SERVICE PERFORMANCE OF BOLTED JOINTS"
Sponsored by Pennsylvania Department of Highways at Lehigh University

| Phase and Topic | Remarks | Tests Performed | Tests to Be Completed | Analytical Work | Reports |
|---|---|---|---|---|---|
| I. Out-of-Flat Large Joints | Authorization: Committee 10 Minutes 10/1/65 (See Project 340) | None | None | | |
| II. Effects of the Variation of Contact Area on slip resistance of Bolted Joints | Authorization: Committee 23 Minutes 10/1/65 Active | 15 joints with clean mill-scale<br>13 joints blast cleaned | 11 joints | | 318.1 |
| III. Effect of slotted and oversize holes upon joint behavior | Authorization: Committee 10 Minutes 10/1/65 Active | 21 joints with over-size and slotted holes | None | Slip behavior and ultimate strength studies | In prep. |

# PROJECT 318

Phases Now Active

| | |
|---|---|
| Phase I | Analysis and pilot tests of large joints which are out-of-flat. Test pieces of large plates, some of which have been purposely warped from true flatness, will be used. Both A325 and A490 bolts would be used in conjunction with these pieces. |
| PhaseII | Analysis and pilot tests of smaller joints to determine the effect of controlled variation of the faying surface on the slip resistance of the joints. |
| Phase III | Analysis and pilot tests of the effect of slotted and oversize holes upon joint behavior. |

# PROJECT 318

Summary of Reports - to December, 1966

Fritz Lab Report

318.1 E. Nester
"Influence of Variation of the Contact Area Upon Slip Resistance of a Bolted Joint"
Master of Science Thesis, July, 1966

# EFFECT OF VARIATION OF THE CONTACT AREA ON THE SLIP RESISTANCE OF BOLTED JOINTS

Fifteen joints were tested to study the relationship between the possible contact area and the slip resistance of bolted joints. The joints were fabricated from 1 inch thick A36 steel plates and had a single line of 4-7/8 inch diameter A325 bolts. The first three joints were normal joints without any washers between the main and lap plates. The other joints tested had 1/2 inch thick round washers placed between the main and lap plates to provide a controlled variation of the contact area as shown in Fig. 1.

A summary of the test results are given in Table 1. The first slip coefficients given in the table are based on the initial bolt tension and the load reached before the first slip. The second slip coefficients are based on the initial bolt tension and the maximum load before a total slip of 0.02 inches was reached. The test results are shown in Fig. 2.

The load-deformation behavior of the three joints with 1-3/4 inch diameter washers is shown in Fig. 3. The behavior shown in Fig. 3 is typical for all of the joints tested with washers between the main and lap plates.

TABLE 1

SUMMARY OF TEST RESULTS

| Specimen No. | Washer Dia. (in.) | Load at 1st Slip (kips) | Max. Load before 0.02" Movement (kips) | Initial Clamping Force (kips) | $K_{s_1}$ (a) | $K_{s_2}$ (b) |
|---|---|---|---|---|---|---|
| CA1-1 | None | 102.8 | 102.8 | 144.2 | 0.36 | 0.36 |
| CA1-2 | None | 82.2 | 82.2 | 145.2 | 0.28 | 0.28 |
| CA1-3 | None | 112.6 | 112.6 | 144.4 | 0.39 | 0.39 |
| Average | | | | | 0.34 | 0.34 |
| CA2-1 | 1-3/4 | 84.1 | 84.1 | 144.6 | 0.29 | 0.29 |
| CA2-2 | 1-3/4 | 92.6 | 92.6 | 145.2 | 0.32 | 0.32 |
| CA2-3 | 1-3/4 | 84.0 | 84.0 | 144.6 | 0.29 | 0.29 |
| Average | | | | | 0.30 | 0.30 |
| CA3-1 | 2-5/8 | 83.5 | 93.3 | 158.2 | 0.26 | 0.29 |
| CA3-2 | 2-5/8 | 64.4 | 87.0 | 144.6 | 0.22 | 0.30 |
| CA3-3 | 2-5/8 | 63.7 | 87.3 | 146.7 | 0.22 | 0.30 |
| Average | | | | | 0.23 | 0.30 |
| CA4-1 | 3-1/2 | 59.3 | 63.4 | 144.9 | 0.21 | 0.22 |
| CA4-2 | 3-1/2 | 57.5 | 62.7 | 145.7 | 0.20 | 0.22 |
| CA4-3 | 3-1/2 | 67.8 | 88.6 | 145.4 | 0.23 | 0.31 |
| Average | | | | | 0.21 | 0.25 |
| CA5-1 | 4-3/8 | 74.4 | 79.4 | 145.2 | 0.26 | 0.27 |
| CA5-2 | 4-3/8 | 75.0 | 75.0 | 144.5 | 0.26 | 0.26 |
| CA5-3 | 4-3/8 | 84.3 | 84.3 | 144.0 | 0.29 | 0.29 |
| Average | | | | | 0.27 | 0.27 |

(a) Based on initial bolt tension and load at 1st slip.

(b) Based on initial bolt tension and maximum load reached before a total slip of 0.02 inch.

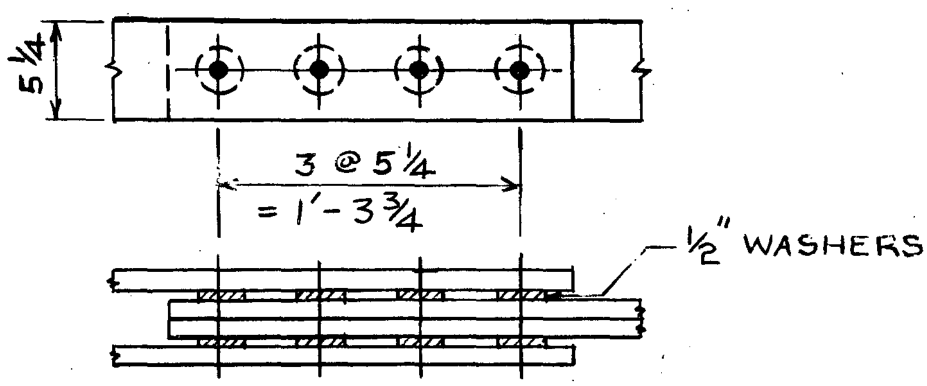



FIG. 1 TEST SPECIMEN WITH WASHERS

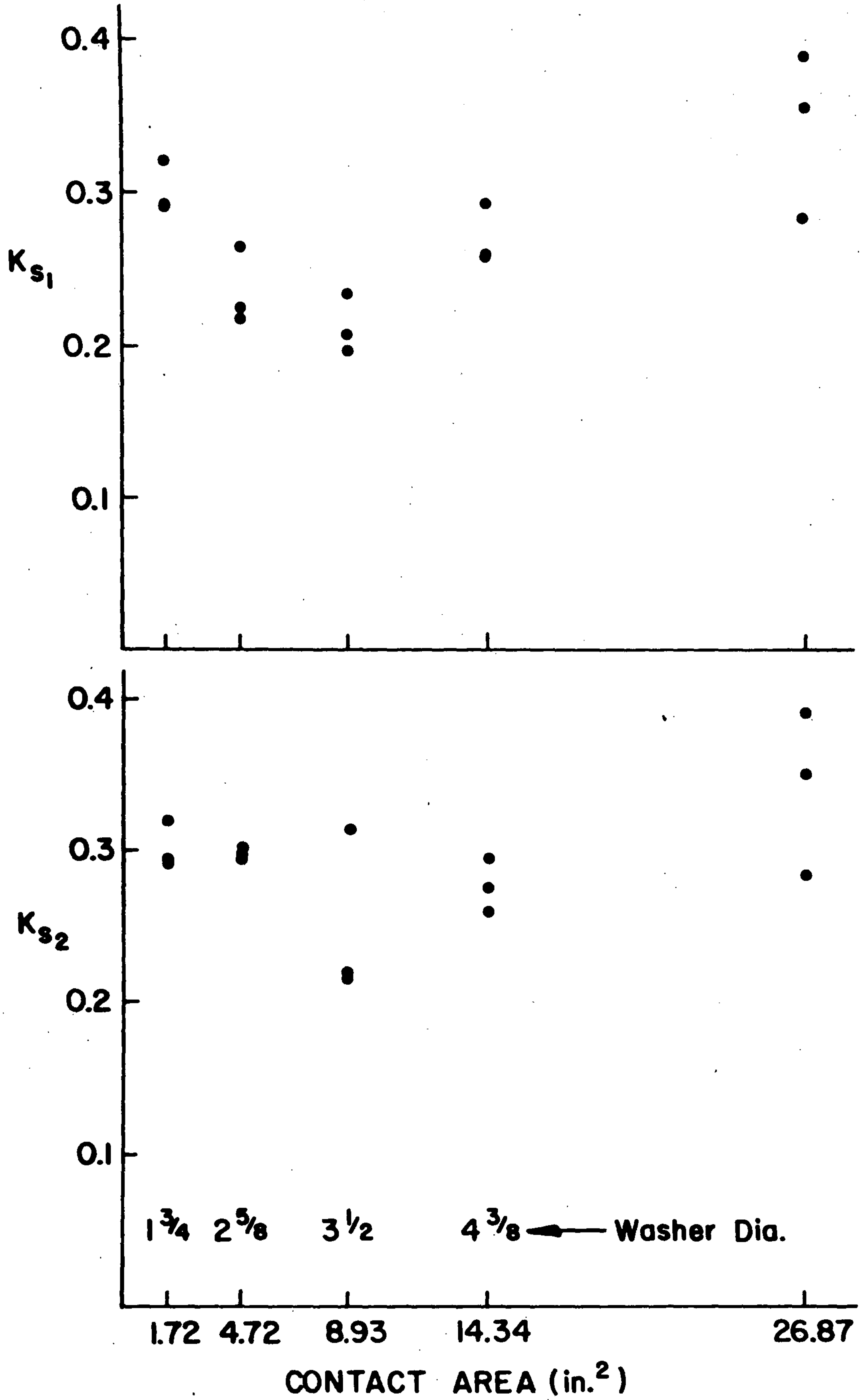



Fig. 2 Slip Coefficient - Contact Area Relationship

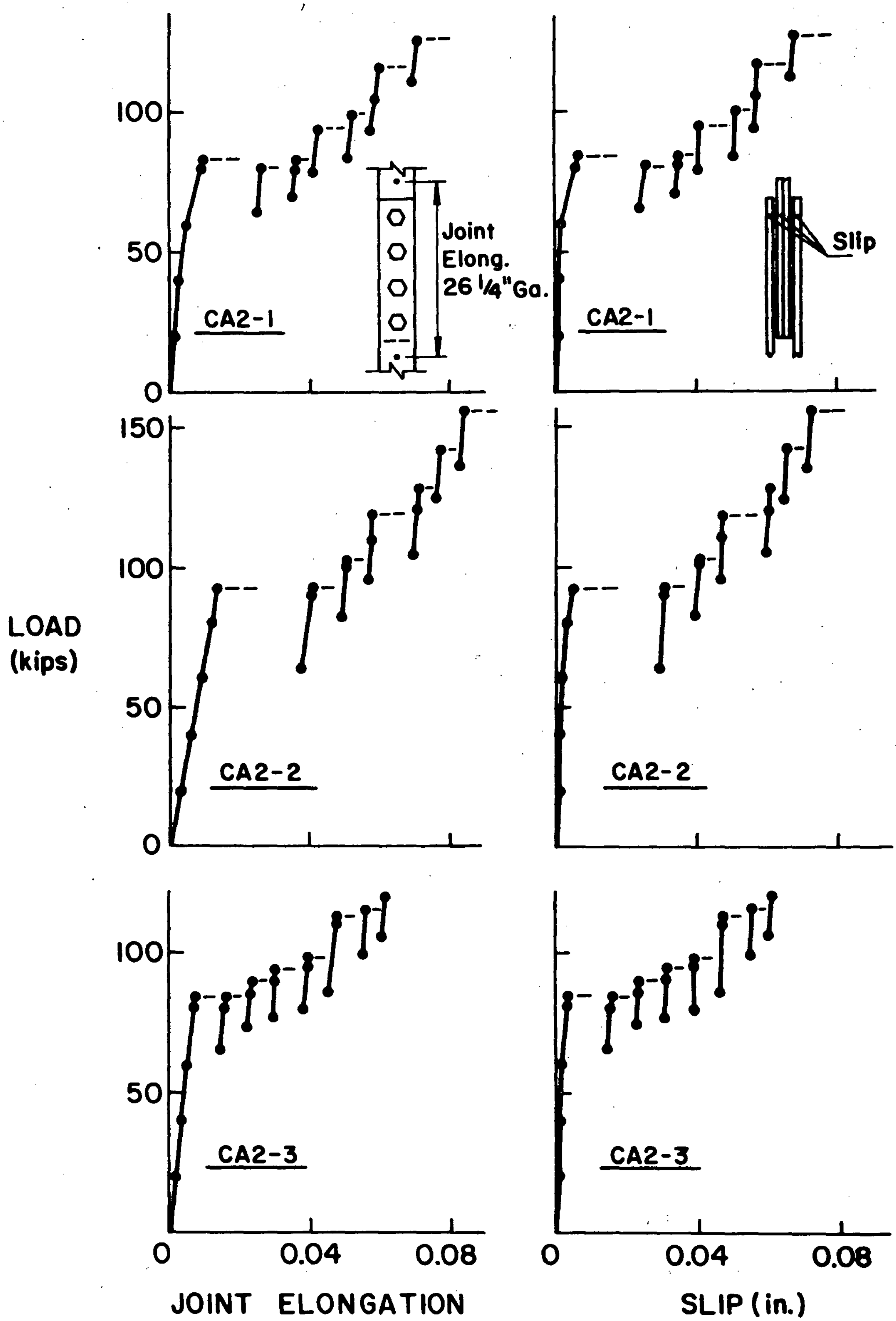



Fig. 3 Load-Deformation Behavior of Joints CA2-1, CA2-2, and CA2-3

PHASE II - Effects of the variation of contact area on slip Resistance of bolted joints.

## 1. Introduction

The effect of the variation of contact surface area and surface treatment on the slip behavior on a bolted joint has been further evaluated during this phase of Project 318. Particular attention was given to blast-cleaned surfaces in conjunction with protective coatings, various contact areas, and fillers. These joints had been tested previously up to the slip load before the faying surfaces were blast-cleaned. Because washers were observed to decrease the slip resistance of bolted joints, six joints were retested with washers inserted between the faying surface and six had the washers replaced by rectangular filler plates.

## 2. Description of test program

Twenty-four joints were prepared for this phase of study. All had blast cleaned faying surfaces. Fifteen joints were four-bolt-in-line specimens fabricated from 1 in. thick A36 steel plates. Blast cleaned filler plates or washers of 1/2 in. thickness were inserted between the main and lap plates of twelve of these joints. Nine additional joints had two lines of four bolts. Three had normal 1/16 in. oversize holes, three had 1/4 in. oversize holes and three had longitudinal slotted holes. The experimental program is summarized in Table 1.

## 3. Instrumentation

Two .0001 in. dial gages and two .001 in. dial gages were used in each test. The relative movement of the joint at one end was measured by .0001 dial gages. The dial gages were bolted to a tab which was tack welded to the main plates and the pointers of the gages rested on a frame which was tack welded to the lap plates at the same level. One dial was mounted on each side to compensate for eccentricity.

Overall joint elongations were measured from points that were one pitch length from the end bolts of the joint.

## 4. Test Results and Analysis

Thirteen joints have been tested to date. The results of these tests are summarized in Table II.

### 4.1 Slip Behavior

The slip behavior observed in the current test program was quite different from that observed with clean mill-scale specimens. The slip occurred gradually and no drop of load nor sudden movement was noted.(Fig.1) Apparently, the blast cleaned surface was rougher than the clean mill-scale surface. Slip could only occur after shearing off the irregularities between contact surface which was a continuous process.

When a bolted joint is subjected to a tensile load, frictional forces are developed along the faying surfaces because the main and lap plates tend to move relative to each other. When the tensile load overcomes the frictional resistance, slip begins to occur. It may develop at the ends of the joint at relatively low loads and progresses inward as the tensile load increased. After the tensile load exceeds the total resistance of the faying surfaces, slip occurs along the whole plane. The slip dial detects local slip and the joint dial records total movement of the joint. Typical test results are summarized in Fig. 1 to 3. These results are also compared with the earlier tests of these joints with clean mill-scale faying surfaces. The results of the blast cleaned joints show that the load-slip and load-elongation curves have the same shape, therefore it was concluded that slip occurs gradually along the entire contact surface in blast cleaned joints and no sudden slip is experienced as with clean mill-scale.

Two values of slip coefficient are listed in Table II. The first ($K_{s1}$) corresponds to the value obtained when the first significant departure from linearity occurred. The second value ($K_{s2}$) was based on the load when the slip was equal to 0.02 inches. Comparable results were discussed previously for clean mill scale surfaces.

## 4.2 Effect of Vinyl Wash Coating

Three joints had a vinyl wash coating applied to blast-cleaned surfaces according to painting specification MIL-C-15328A Figure 2 compares the behavior of the blast-cleaned joint with vinyl wash applied to its behavior with the plain mill-scale. The application of the vinyl wash significantly reduced the slip resistance as a comparison of the results summarized in Table II indicates. The slip coefficient decreased from 0.65 to about 0.30. However, as is apparent in Fig. 2 and Table III, the blast cleaned vinyl wash specimen had a slip resistance that was equal to clean mill-scale.

### 4.3 Effect of Filler Plates

Five joints were tested with 1/2 inch filler plates inserted between the faying surfaces. Two had the fillers tack welded to the main plates. There was no difference in the slip resistance of these joints. The presence of the filler plates reduced the slip resistance of blast cleaned joints from 0.65 to 0.37 at first slip and from 0.74 to 0.52 for a slip of 0.02 in. Figure 3 compares the behavior of joint CA2-1 with filler plates to the behavior of clean mill-scale tests. The influence of the filler plates is apparent. Table II also compares the tests of blast cleaned joints with filler plates with the test results of joints with clean mill scale faying surfaces where round washers were inserted between the faying surface. The effect of the insert was similar in that a reduction in slip resistance was observed for both washers and rectangular fillers.

### 4.4 Effect of Slotted Holes

Only one blast cleaned slotted hole joint has been tested. The result of this test showed that the slip resistance decreased to a value of 0.50 as compared to 0.65 for control joints. Similar behavior was observed with clean mill scale specimens.

## 4.5 Effect of Exposure and Rusting on Slip Resistance

Three joints were allowed to rust in open air after blast-cleaning. One joint was tested after two months exposure. The joint was bolted up without wire brushing the rusted surface. The result shown in Table II indicates that there is a decrease in the slip coefficient from 0.65 to 0.43. This still exceeds the slip resistance of the clean mill-scale specimens. The slip behavior of the rusted joint was similar to clean mill scale joints in that a sudden movement occurred. Two additional joints are being exposed and will be tested after six months and one year exposure.

TABLE 1 TEST PROGRAM FOR PHASE II AND III

| JOINT SERIES | NO. OF JOINTS | BOLT DIA. (IN.) | HOLE DIA. (IN.) | JOINT WIDTH (IN.) | $\frac{An}{As}$ | REMARKS | SURFACE TREATMENT |
|---|---|---|---|---|---|---|---|
| CA1 | 3 | $\frac{7}{8}$ | $\frac{15}{16}$ | 5¼ | 1.79 | Control tests | Blast Cleaned |
| CA2 | " | " | " | " | " | Filler plates | Blast Cleaned |
| CA3 | " | " | " | " | " | 3½-in. wahsers | Blast Cleaned |
| CA4 | " | " | " | " | " | 3½-in. wahsers tack welded | Blast Cleaned |
| CA5 | " | " | " | " | " | Filler plates-tack welded | Blast Cleaned |
| OH1 | 3 | 1 | $1\frac{1}{16}$ | 6.40 | 0.68 | | Blast Cleaned Vinyl Wash |
| OH2 | " | " | 1¼ | 6.78 | " | Oversize holes | Blast Cleaned-Allowed to rust |
| OH3 | " | " | " | " | " | " | Hold in researve |
| OH4 | " | | $1\frac{5}{16}$ | 6.65 | " | " | Hold in researve |
| SH1 | 3 | 1 | - | 6.40 | " | Slots parallel to load | Blast Cleaned |

TABLE II

| Specimen No. | Load at 1st Slip Kips | Max. Load Before .02" Movement Kips | Initial Clamping force Kips | $K_{s_1}$ | $K_{s_2}$ | Remarks |
|---|---|---|---|---|---|---|
| CA1-1 | 170 | 200 | 144 | 0.59 | 0.70 | Blast Cleaned Faying Surface |
| CA1-2 | 200 | 225 | 144 | 0.70 | 0.77 | |
| CA1-3 | 190 | 212 | 144 | 0.66 | 0.74 | |
| Average | | | | 0.65 | 0.74 | |
| OH1-1 | 290 | 303 | 463 | 0.32 | 0.33 | Blast Cleaned then treated with Vinyl wash MIL-C-15328-A |
| OH1-2 | 200 | 210 | 360 | 0.28 | 0.30 | |
| OH1-3 | 270 | 280 | 489 | 0.28 | 0.29 | |
| Average | | | | o.29 | 0.31 | |
| CA2-1 | 120 | 145 | 144 | 0.42 | 0.51 | Blast Cleaned with ½ inch filler plates |
| CA2-2 | 100 | 140 | 144 | 0.35 | 0.49 | |
| CA2-3 | 100 | 155 | 144 | 0.35 | 0.54 | |
| Average | | | | 0.37 | 0.52 | |
| CA5-1 | 110 | 160 | 144 | 0.39 | 0.56 | Blast Cleaned with ½" filled plates tack welded to main plate |
| CA5-3 | 80 | 130 | 144 | 0.28 | 0.46 | |
| Average | | | | 0.34 | 0.51 | |
| OH2-2 | 310 | 310 | 360 | 0.43 | 0.43 | Blast Cleaned and exposed to industrial climate for 2 months (rusted) |
| SH1-2 | 360 | 360 | 360 | 0.5 | 0.5 | Blast Cleaned with longitudinal slots. |

TABLE III

| Specimen No. | Surface Condition | | Slip Coefficient | | | |
|---|---|---|---|---|---|---|
| | Previous Tests | Recent Test | Previous Test $K_{s_1}$ | Previous Test $K_{s_2}$ | Recent Test $K_{s_1}$ | Recent Test $K_{s_2}$ |
| CA1 | Mill-scale | Blast Cleaned | 0.34 | 0.34 | 0.65 | 0.74 |
| OH1 | Mill-scale | Blast Cleaned with Vinyl wash | 0.29 | 0.29 | 0.29 | 0.31 |
| CA2 | Mill-scale 1-3/4" washer | Blast Cleaned Filler Plates | 0.30 | 0.30 | 0.37 | 0.52 |
| CA5 | Mill-scale 4-3/8" washers | Blast Cleaned Filler Plates Tack welded | 0.27 | 0.27 | 0.34 | 0.51 |
| OH2-2 | Mill-scale | Blast Cleaned rusting for 2 months | 0.29 | 0.29 | 0.43 | 0.43 |
| SH1-2 | Mill-scale | Blast Cleaned | 0.19 | 0.19 | 0.5 | 0.5 |

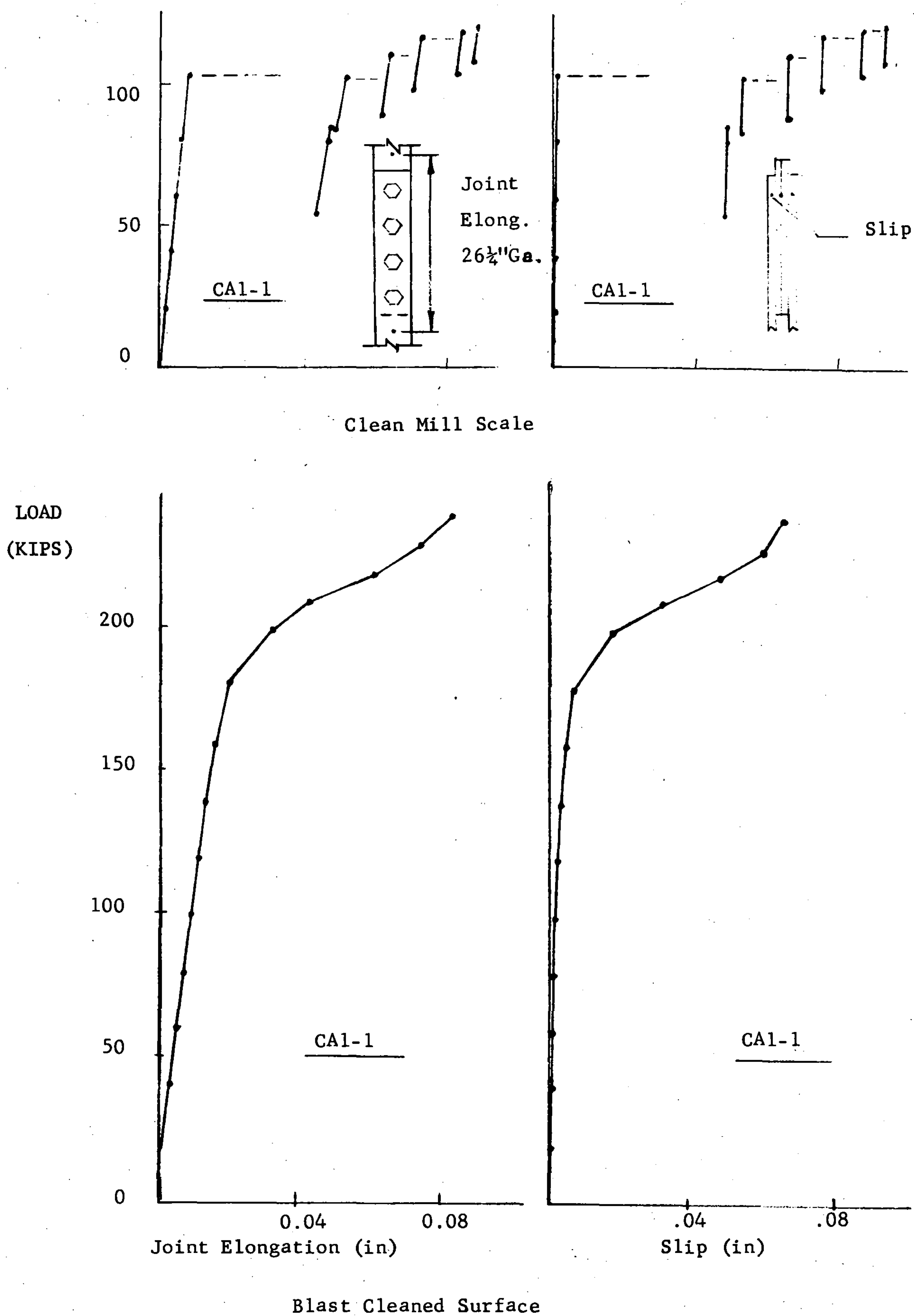
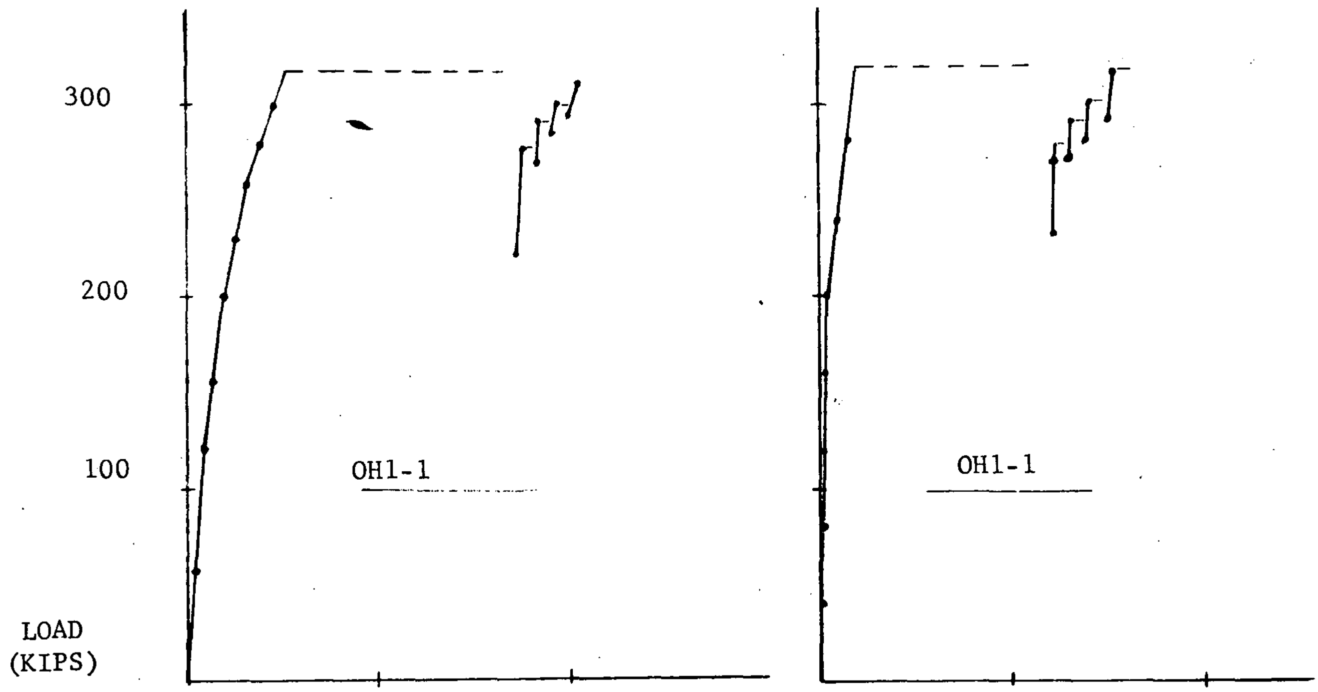
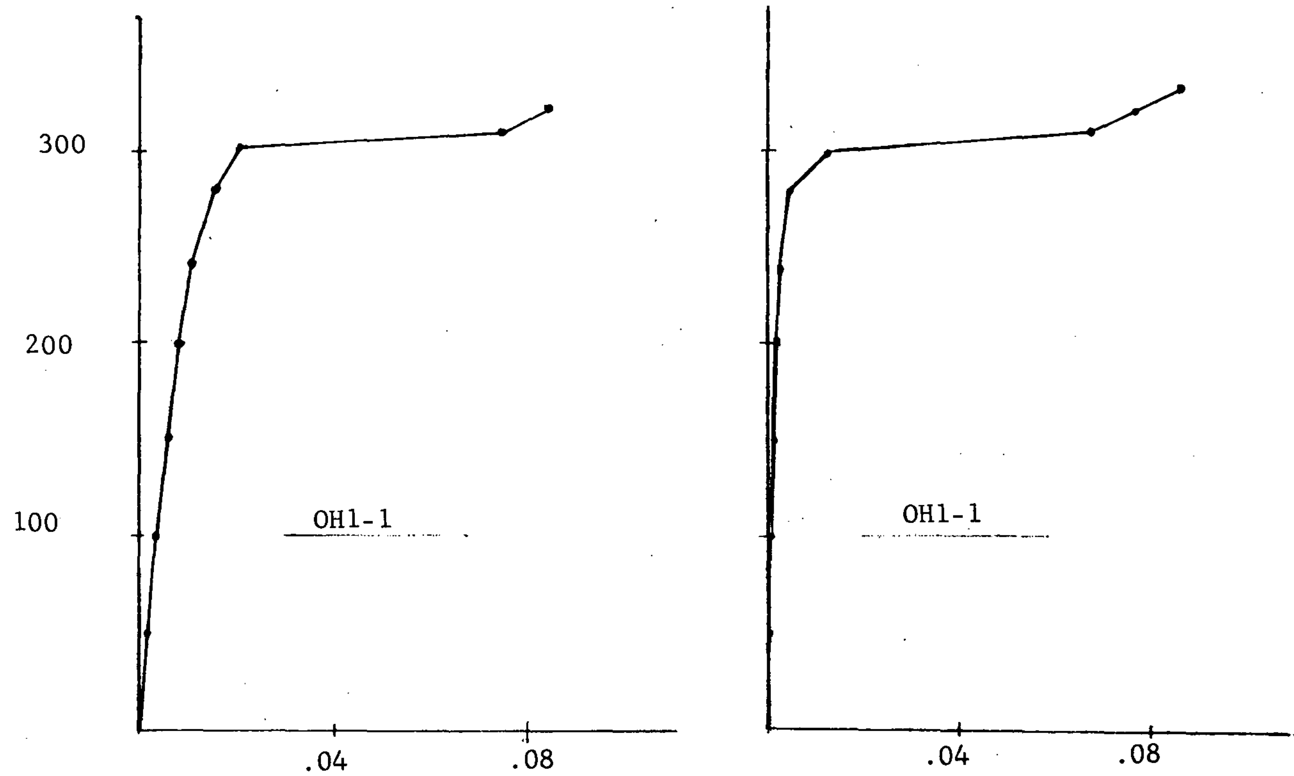



Figure 1. Load Deformation Behavior of Joint CA1-1

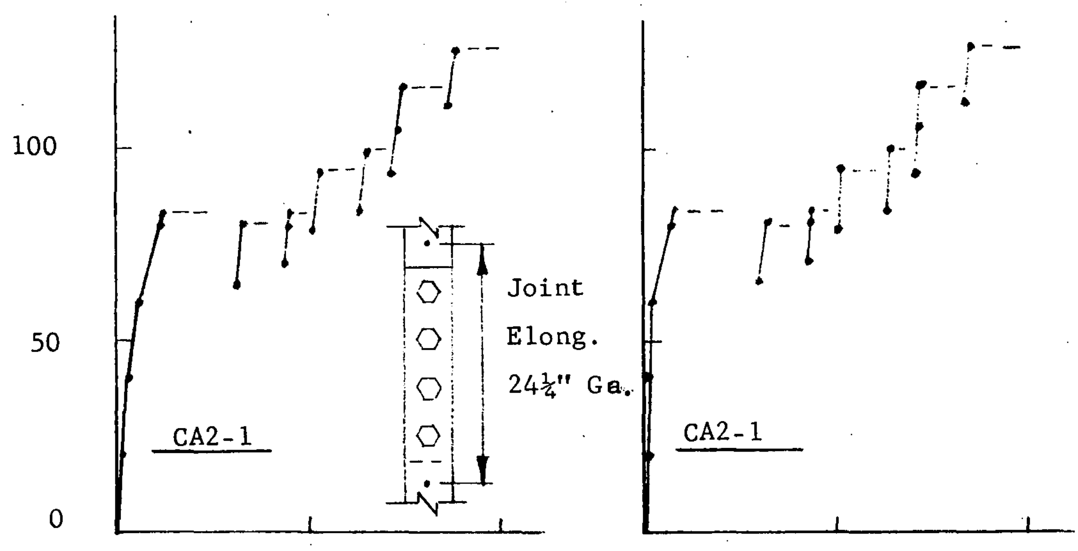



Clean Mill Scale

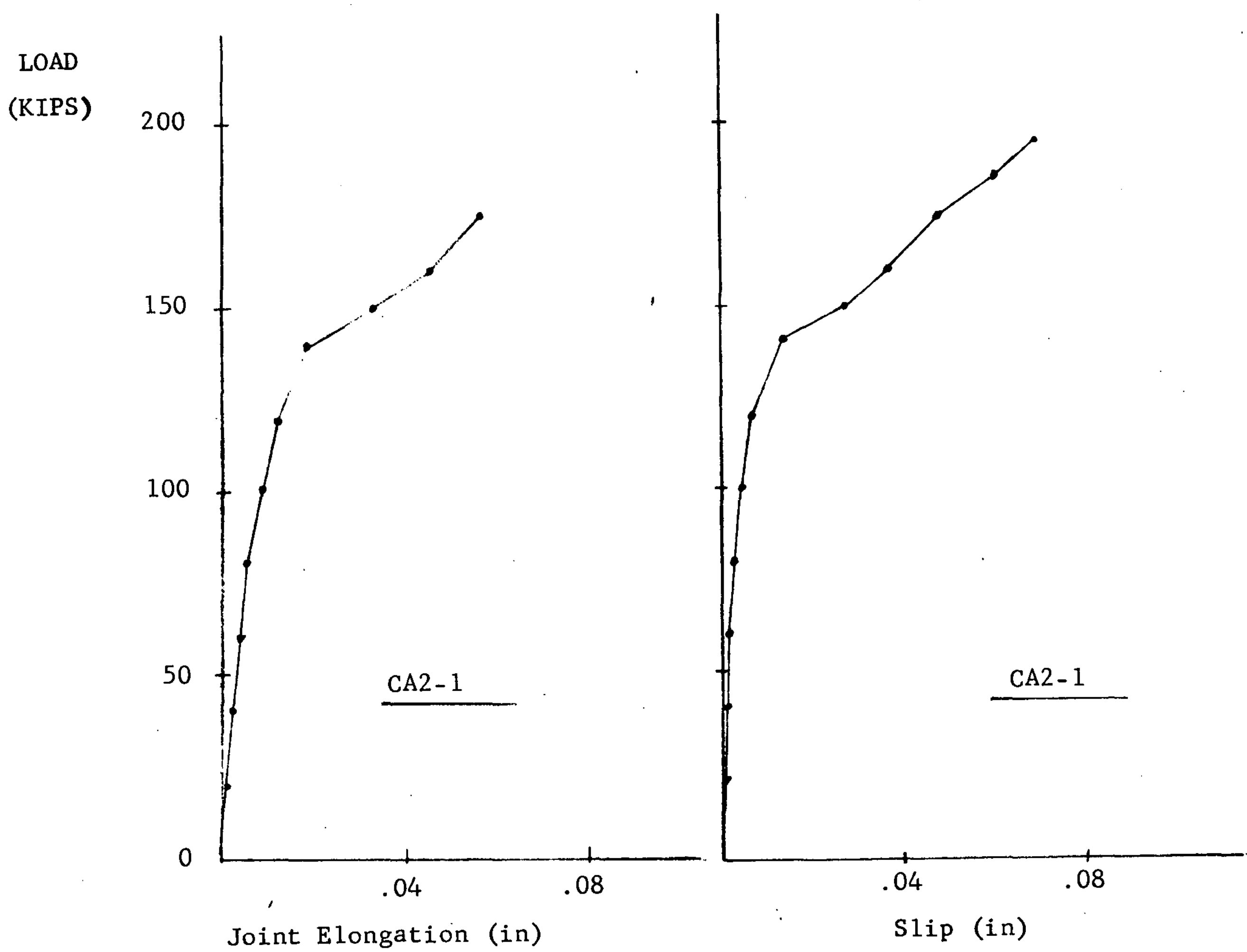



Blast Clean Surface With Vinyl Wash Coating

Figure 2. Load Deformation Behavior of Joint OH1-1




Clean Mill Scale with 1-3/4" Washers




Blast Cleaned surface with ½" Filler plate

Figure 3. Load Deformation Behavior of Joint CA2-1

## Project 318 - Service Performance of Bolted Joints

Phase III - The Effect of Slotted and Oversize Holes on the Performance of Bolted Joints.

During the past two years a study has been underway at Fritz Engineering Laboratory to determine what effect oversize and slotted holes would have on the performance of a bolted joint. A total of 21 bolted joints were tested. Twelve of these specimens contained oversize holes and nine contained slotted holes. They were fabricated from 1-inch thick A36 steel plates and were fastened with 1" A325 bolts connecting 4 plies of plate that had 2 faying surfaces of tight mill scale.

### Oversize Holes

Twelve bolted joints were tested to study the relationship between amount of oversize and the slip resistance of bolted joints. They were designed as friction-type joints with the net area equal to 70% of the bolt shear area. Also observed during the study was the effect of the amount of oversize on bolt installation, whether or not washers are needed, loss in bolt tension after installation and changes in bolt tension during testing.

Three of the specimens had hole diameters of 1-1/16 inches. This provided the maximum hole clearance of 1/16 inch as specified in the current specifications and provided the control specimens for comparative purposes. Six specimens had hole diameters of 1-1/4 inches which provided a hole clearance of 1/4" that was 4 times the specified maximum hole clearance. Three of these were bolted up without washers and three were bolted up with washers under the nut. Three specimens had hole diameters of 1-5/16 inches which provided a hole clearance that was 5 times the specified maximum hole clearance.

It was observed that there was no significant change in the slip coefficient for the specimens with the 1-1/4" holes as compared with the control specimens. (See Table 1) However, there was a noticeable drop in the slip coefficient for the specimens with the 1-5/16 inch holes. Using the standard installation procedure of snug tight plus one-half turn, the bolts achieved a load higher than the specified minimum load in the 1-1/16 inch and 1-1/4 inch diameter holes. The specified minimum load was not attained in the 1-5/16 inch diameter holes with a washer installed under the nut using the standard installation technique. When washers were placed under both the head and the nut, a bolt preload slightly higher than the specified minimum load was achieved.

Both the bolt head and nut caused a small indentation in the plate material around the holes that were 1-1/16 inch in diameter. In the 1-1/4 inch diameter holes where washers were not installed under the nuts, severe galling occurred in the plate around the holes under the nuts. When washers were installed under the nuts in the 1-1/4 inch holes, this severe galling did not occur. A slight indentation occurred under the bolt heads in the plate around the holes but was not of consequence. When the bolts were installed in the 1-5/16 inch holes with washers under the nuts, severe indentations occurred in the plate under the nut heads so that the required preload was not attained. When bolts were installed in the 1-5/16 inch holes with washers under both the heads and the nuts, no damage occurred at either end of the holes.

The amount of hole oversize had no significant effect on either the loss-in-tension of the bolts after installation or in the changes in bolt tension during testing.

Slotted Holes

Nine bolted joints were tested to evaluate the effect of slotted holes on the slip performance and ultimate joint strength. The slotted holes were placed in the middle plies and were 2-9/16 inches long and 1-1/16 inches wide. The holes in the outside plies were the standard 1-1/16 inches in diameter. All nine joints were assembled with the bolts centered in the slots.

Three of these specimens had slotted holes placed parallel to the line of load. They were designed as friction-type joints. The tests provided an opportunity to evaluate the effect of slotted holes on the slip resistance. These joints showed a significant decrease in the slip coefficient. (See Table II)

Six specimens had slotted holes perpendicular to the line of load and were proportioned as bearing-type joints. Three joints had the net area equal to the bolt shear area and three had an $A_n/A_s$ ratio of 1.36. They were tested to study the effect of slots and of varying joint properties on the slip resistance and ultimate strength. These six joints also showed a significant drop in the slip coefficient. The ultimate strength based on either plate or bolt failure was not reduced.

The presence of the slots in either direction had no significant effect on either the loss-in-tension of the bolts after installation or in the changes in bolt tension during testing.

A summary of the results of tests on the friction type joints is given in Table I. The slip coefficients given in the table are based on the initial bolt tension and the load at the first major slip.

A summary of the tests on the bearing joints is given in Table II.

TABLE 1

SUMMARY OF TEST RESULTS - FRICTION JOINTS

| Joint No. | Hole Diameter | Initial Bolt Tension | Initial Slip Load | Slip Coeff. ($K_s$) |
|---|---|---|---|---|
| OH1-1 | 1 1/16" | 551.6 | 314.5 | .285 |
| OH1-2 | 1 1/16" | 558.0 | 327.5 | .293 |
| OH1-3 | 1 1/16" | 570.4 | 322.5 | .283 |
| Average | | | | .287 |
| OH2-1 | 1¼" | 522.8 | 274.5 | .263 |
| OH2-2 | 1¼" | 442.0 | 242.5 | .275 |
| OH2-3 | 1¼" | 474.5 | 295.0 | .311 |
| Average | | | | .282 |
| OH3-1 | 1¼" | 495.2 | 286.5 | .290 |
| OH3-2 | 1¼" | 482.8 | 267.0 | .277 |
| OH3-3 | 1¼" | 473.5 | ~~333.5~~ 260.0 | ~~.352~~ .274 |
| Average | | | | ~~.306~~ .280 |
| OH4-1 | 1 5/16" | 502.6 | 265.0 | .264 |
| OH4-2 | 1 5/16" | 531.2 | 253.5 | .238 |
| OH4-3 | 1 5/16" | 533.1 | 236.0 | .222 |
| Average | | | | |
| SH1-1 | Slotted | 504.0 | 185.5 | .184 |
| SH1-2 | Slotted | 524.1 | 199.0 | .190 |
| SH1-3 | Slotted | 549.5 | 237.0 | .215 |
| Average | | | | .196 |

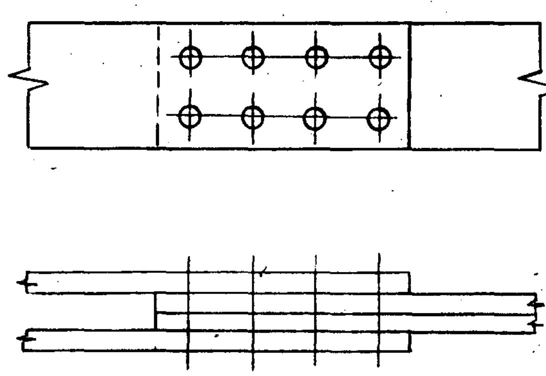


Fig. 1 Oversize Hole Test Specimen

# TABLE II

## SUMMARY OF TEST RESULTS - BEARING JOINTS

### TABLE II A - PLATE FAILURE

| Joint No. | An/As | Slip Load | $K_s$ | Ultimate Load | Ultimate Plate Stress | Coupon Ult. Plate Stress |
|---|---|---|---|---|---|---|
| SH2-1 | 1.00 | 248 | .237 | 820 | 65.9 | 61.1 |
| SH2-2 | 1.00 | 220 | .192 | 854 | 68.6 | 61.1 |
| SH2-3 | 1.00 | 262.5 | .250 | 852 | 68.9 | 62.0 |
| Average | | | .226 | | 67.8 | 61.4 |
| SH3-1 | 1.36 | 200 | .170 | 1104 | 63.6 | 61.3 |

### TABLE II B - BOLT FAILURE

| Joint No. | An/As | Slip Load | $K_s$ | Ultimate Load | Ultimate Shear Stress | Tension Jig Shear Stress |
|---|---|---|---|---|---|---|
| SH3-2 | 1.36 | 210 | .221 | 1000 | 79.5 | 74.9 |
| SH3-3 | 1.36 | 214 | .223 | 1006 | 80.0 | 74.9 |
| Average | | | .205 | 1003 | 79.8 | 74.9 |

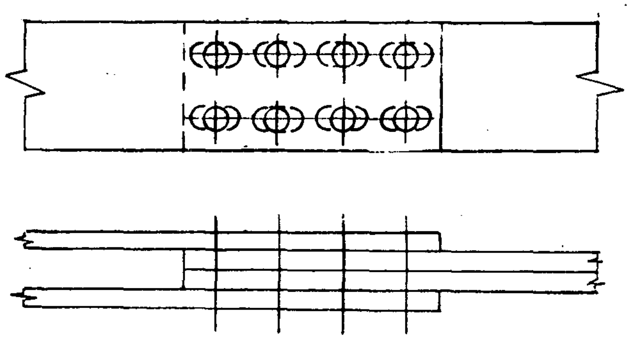


Fig. 2a Slots Parallel to Direction of Load

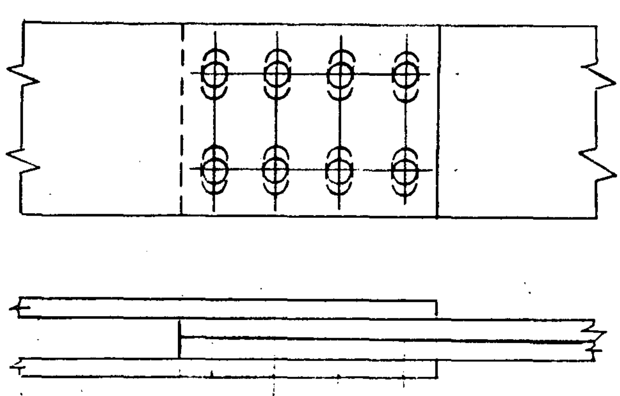


Fig. 2b Slots Perpendicular to Direction of Load

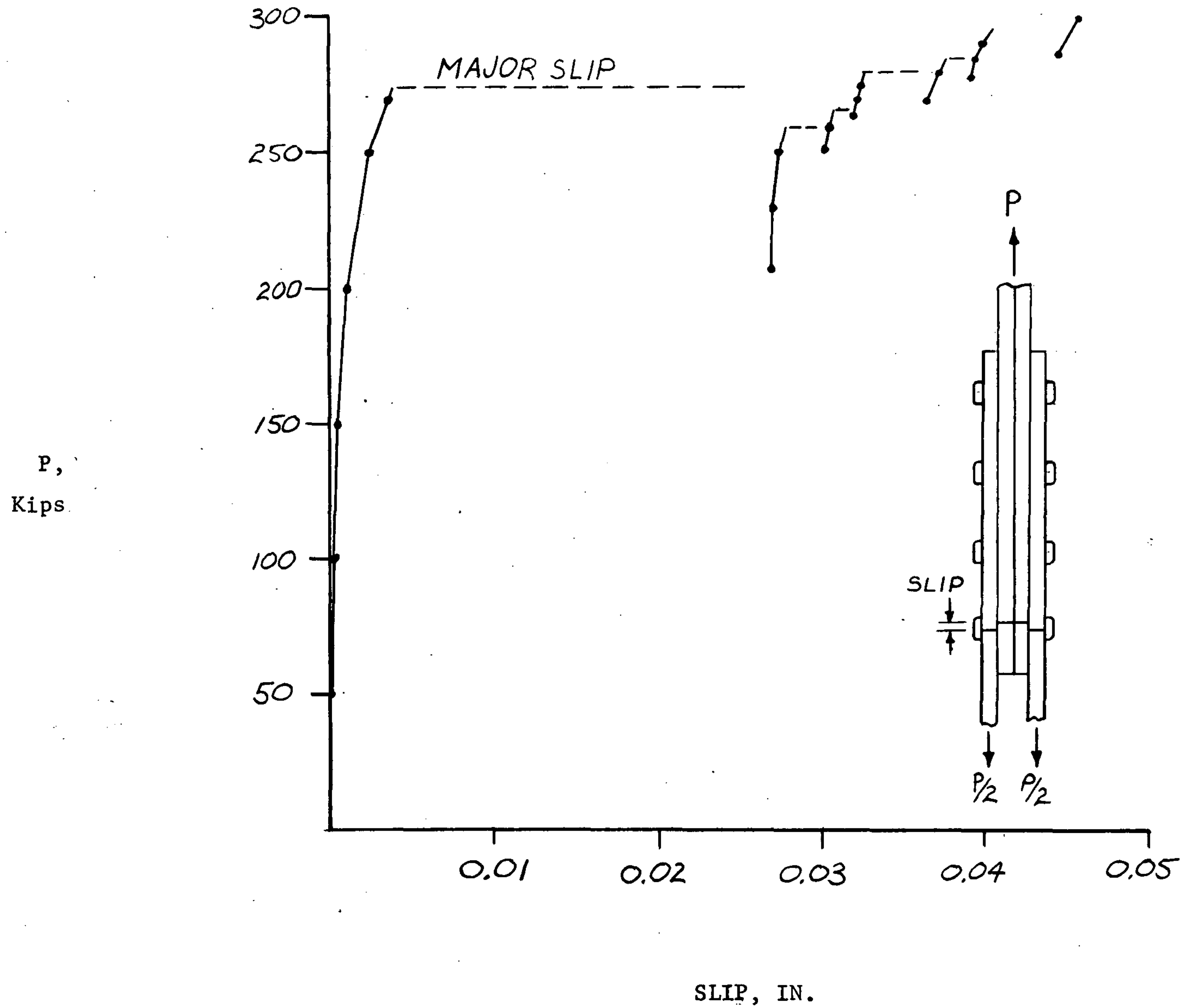
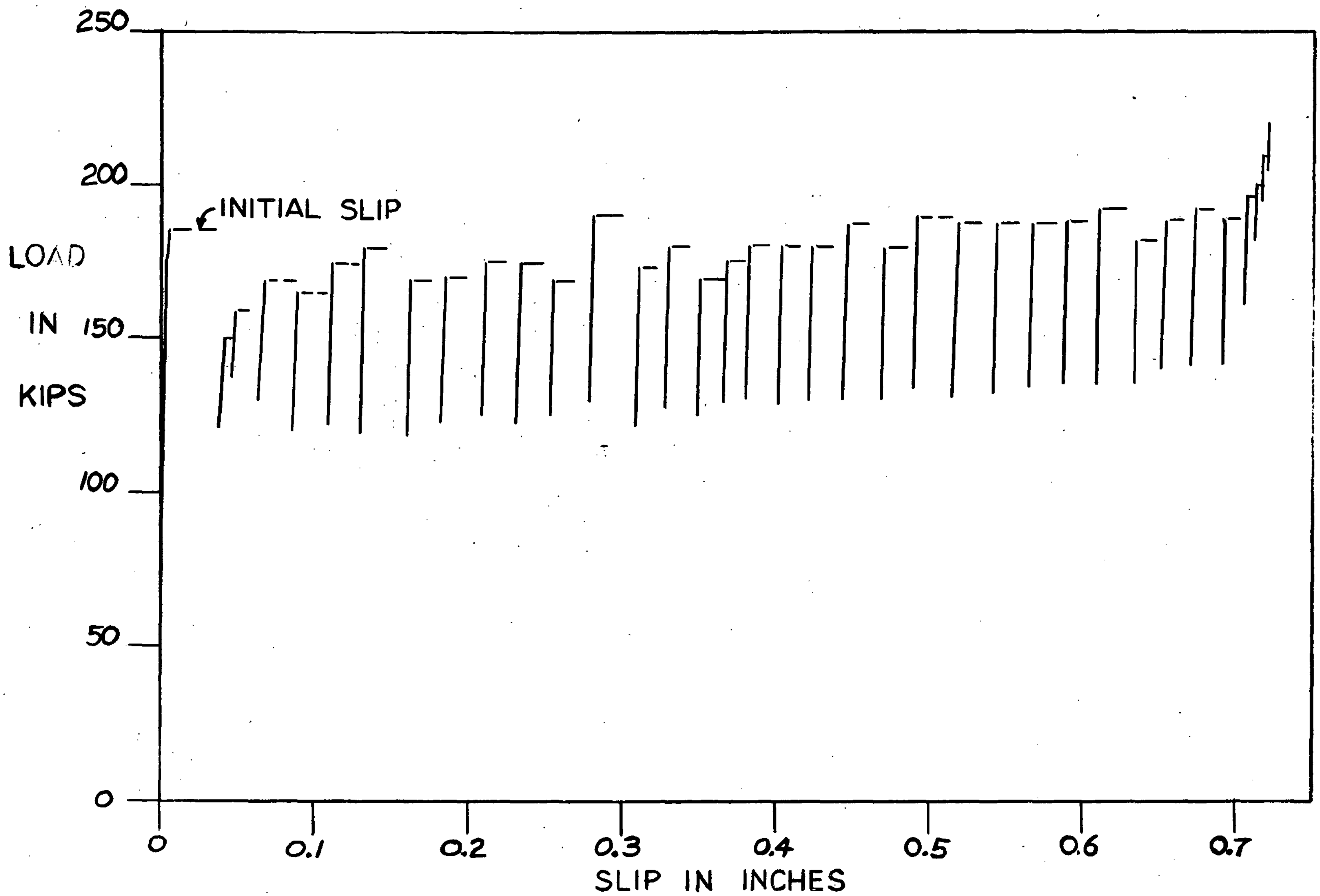



FIG. 3 Joint Load-Slip Characteristics of Joint OH2-1

318.25

FIG. A LOAD-SLIP DIAGRAM OF JOINT SH1-1

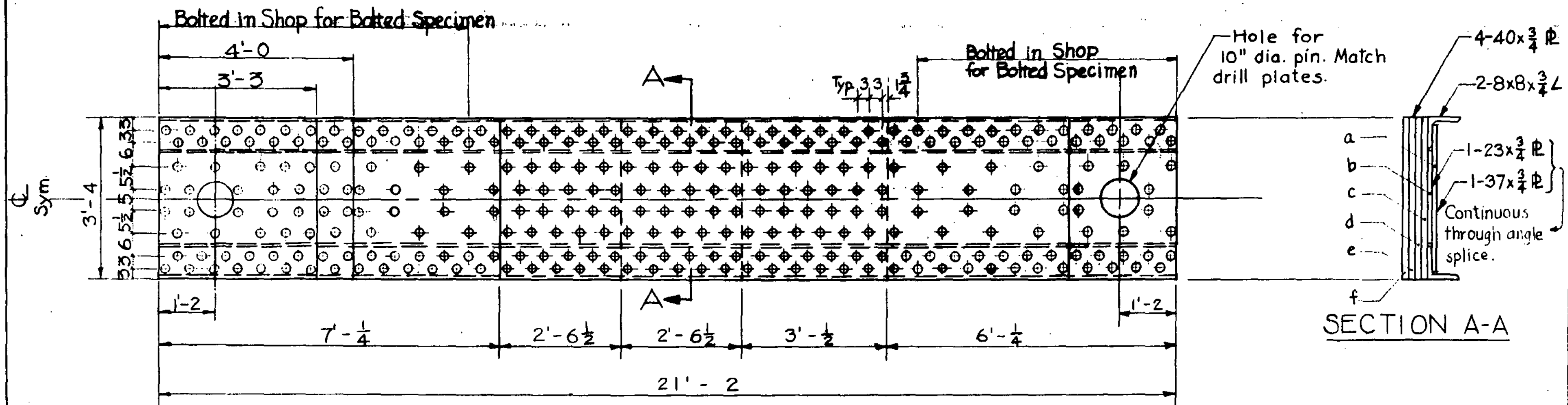


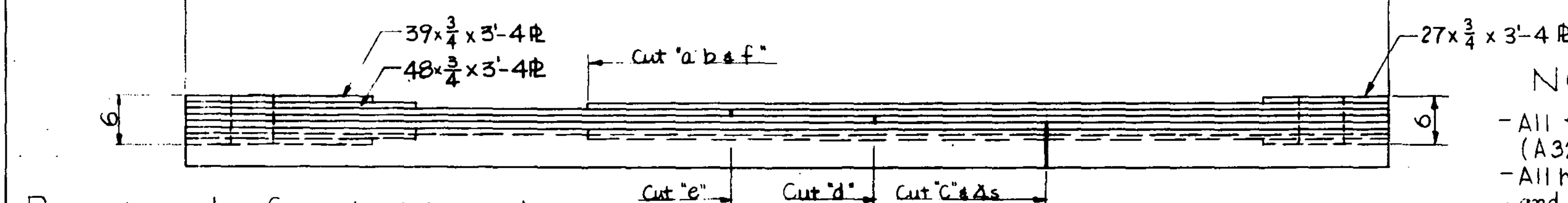
STATUS OF VARIOUS PHASES ON PROJECT 340
"STUDIES OF SIMULATED BRIDGE JOINTS"

Sponsored by Louisiana Department of Highways at Lehigh University

| Phase and Topic | Remarks | Tests Performed | Tests to be Completed | Anayltical work | Reports |
|---|---|---|---|---|---|
| I. Effects of Out-of-flatness | Committee 23 Minutes 1/31/67 | Calibration of device to evaluate force to flatten plates | Installation studies in simulated joints | Analysis of forces required to flatten plates | None |
| II. Control Test | Committee 23 Minutes 1/31/67 | None | 5 control joints, 2 riveted and 3 bolted calibration studies | | None |
| III. Full size simulated Joint Test | Committee 23 Minutes 1/31/67 | None | 1 riveted joint 1 bolted joint | Load partitition in shingle joints | None |

340.1




Required : 1 Joint fastened with A325 bolts
1 Joint fastened with A502 Gr.1 rivets

## NOTES:

- All fasteners shall be 7/8"φ (A325 bolts or A502 Gr.1 rivets.)
- All holes shall be subdrilled and reamed.
- Angles and plate shall be V55.
- No paint.
- See attached sheets

# PROPOSED TEST JOINTS

Scale: 1/2" = 1'-0

LARGE BOLTED CONNECTIONS

PROJECT 340

LEHIGH UNIVERSITY

Sheet 1

Dwn. July 19 1966 GLK.
Corr. Jan. 30, 1967 N.Y.
Corr. Feb. 2, 1967 N.Y.