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Summary report to the research council on riveted and bolted structural joints, December 1966

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LARGE BOLTED JOINTS

SUMMARY REPORT TO

THE RESEARCH COUNCIL ON

RIVETED AND BOLTED

STRUCTURAL JOINTS

by

Project Staff

(Not for publication)

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LEHIGH UNIVERSITY STATUS OF VARIOUS PHASES

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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	
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	317.3 317.5
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	

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
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July, 1966

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

BOLTED HIGH-STRENGTH STEEL JOINTS, PROJECT 318
LEHIGH UNIVERSITY STATUS OF VARIOUS PHASES

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	None	Installation studies in warped joints		
II. Effects of the Variation of Contact Area on slip resistance of Bolted Joints	Authorization: Committee 23 Minutes 10/1/65 Active	8 joints	16 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	

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

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.[2] Thus, the test program involving large joints was set up.

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 An/As ratio, where An is the net area of either the main or lap plates and As 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. In A514 steel joints, it is not until one gets to joints of this length that any substantial amount of load redistribution 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 from above. At a given joint length, the ultimate strengths of joints with decreasing values of An/As are computed. The process must start in the fastener failure region, that is, at a value of An/As 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 An . σ_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 effect 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 An/As = ∞. Shown between this limiting line and the other limit, the plate failure boundary, are joint strength curves for An/As 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 An/As of 0.53 results. As shown in Fig. 3 where the same boundary is plotted as An/As 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.[3] The An/As value in this case would be 0.67. Examining Fig. 3 again, it can be seen that plate failure would control 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 An/As curves of 0.62 and ∞ cover a range of shear stress values of only 78.5 ksi to 91.5 ksi. This means that the load carried by a joint with An/As = 0.62 will not be greatly less than a joint at the same length with, say, An/As = 1.00. The theoretical values of load 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 a 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 (An/As = 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 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 occurred. 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. Because of this behavior, the data from this test were not used in analyzing the slip behavior of these joints.

The pilot joints behaved in a very similar fashion to that described here. None, however, 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" (Ks). This is defined as

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

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 Ks 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 10½-in. respectively. The values of Ks for these two joints also are identical.

The mean value of Ks 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 redistribution of load would occur among the fasteners in joints of this short length. Hence, predicted ultimate loads were simply 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 fastener 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.

Specimens J072, J132, J172 and J252 all failed by an apparent simultaneous shearing of all of the fasteners. Although the end fasteners theoretically should, and probably did, fail first, the high level of load in the remaining bolts meant that they were not able to carry the additional load from the first failed fastener. That the failure was as hypothesized has been observed from re-assembled sheared bolts. Although failure was by apparent simultaneous shear of all fasteners, it is obvious from the bolt deformations that an end fastener was governing.

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OR A490 BOLTS, 1964

TABLE 1

JOINT DIMENSIONS AND RESULTS

PILOT TESTS

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
Shear Area (As)	$in.^2$	15.90	15.90	15.90	15.90	15.90	15.90	12.57	12.57	12.57	12.57
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	$in.^2$	11.28	12.98	13.80	14.51	15.41	16.31	13.93	14.63	15.24	15.95
Net Area (An)	$in.^2$	6.40	8.07	8.90	9.66	10.52	11.40	9.58	10.25	10.85	11.55
An/As	-	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	800	1010	1050	1050	1050	1050	1210	1210	1210	1210
Actual	kips	860	1052	1064	1056	1062	1074	1238	1228	1206	1220
Failure Mode	-	Plate	Bolts	Bolts	Bolts	Bolts	Bolts	Bolts	Bolts	Bolts	Bolts

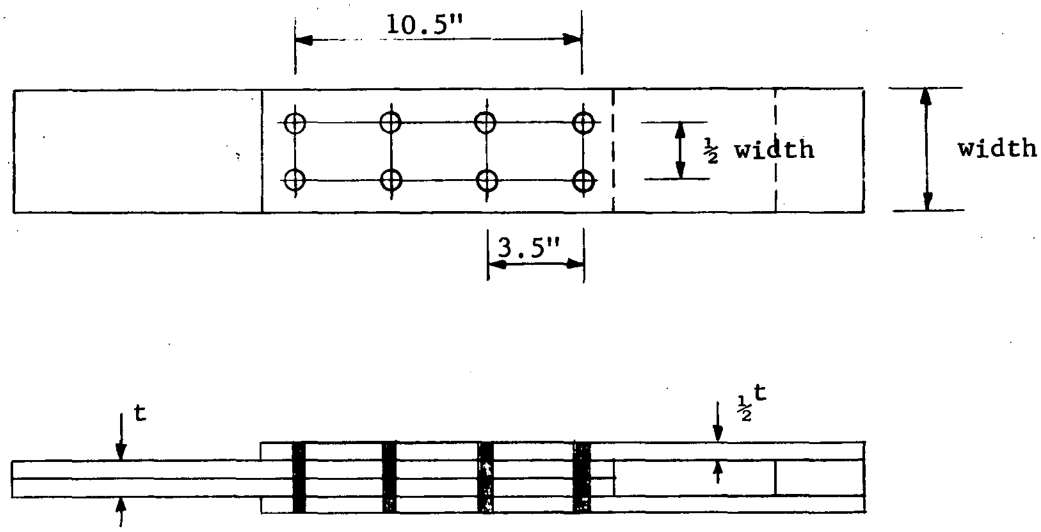
TABLE 2

JOINT DIMENSIONS AND TEST RESULTS

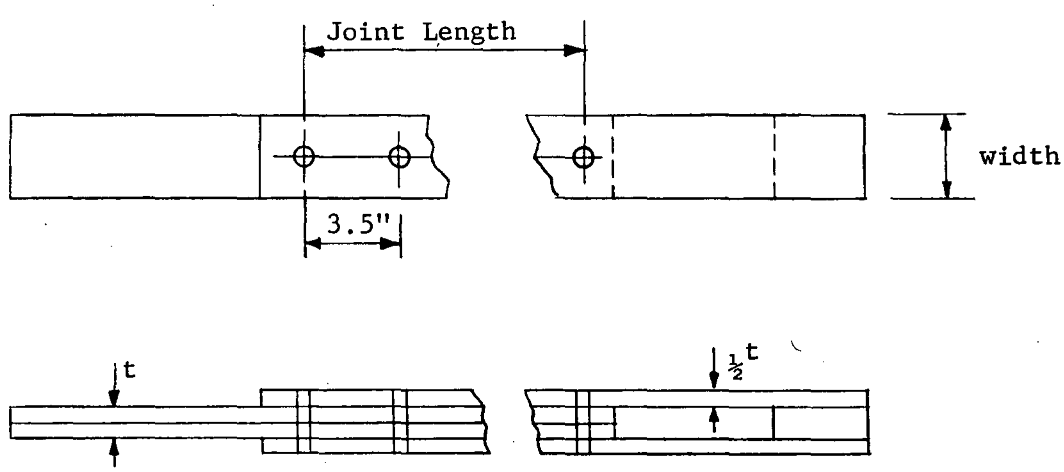
LARGE JOINTS

Item	Units	J071	J072	J131	J132	J171	J172	J251	J252
Bolts 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
Shear Area (As)	in^2	8.41	8.41	15.63	25.84	20.44	20.44	30.07	30.07
Plate 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	in^2	7.82	9.58	12.99	28.55	16.48	20.40	28.35	37.55
Net Area (An)	in^2	5.92	7.66	11.08	23.70	14.55	18.52	24.55	33.73
An/As	-	0.70	0.91	0.71	0.91	0.71	0.90	0.82	1.12
Slip 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
Ultimate Load									
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

* NOT DEFINED
JOINT WAS WARPED



Pilot Joints



Large Joints

Fig. 1 Geometry of Test Joints

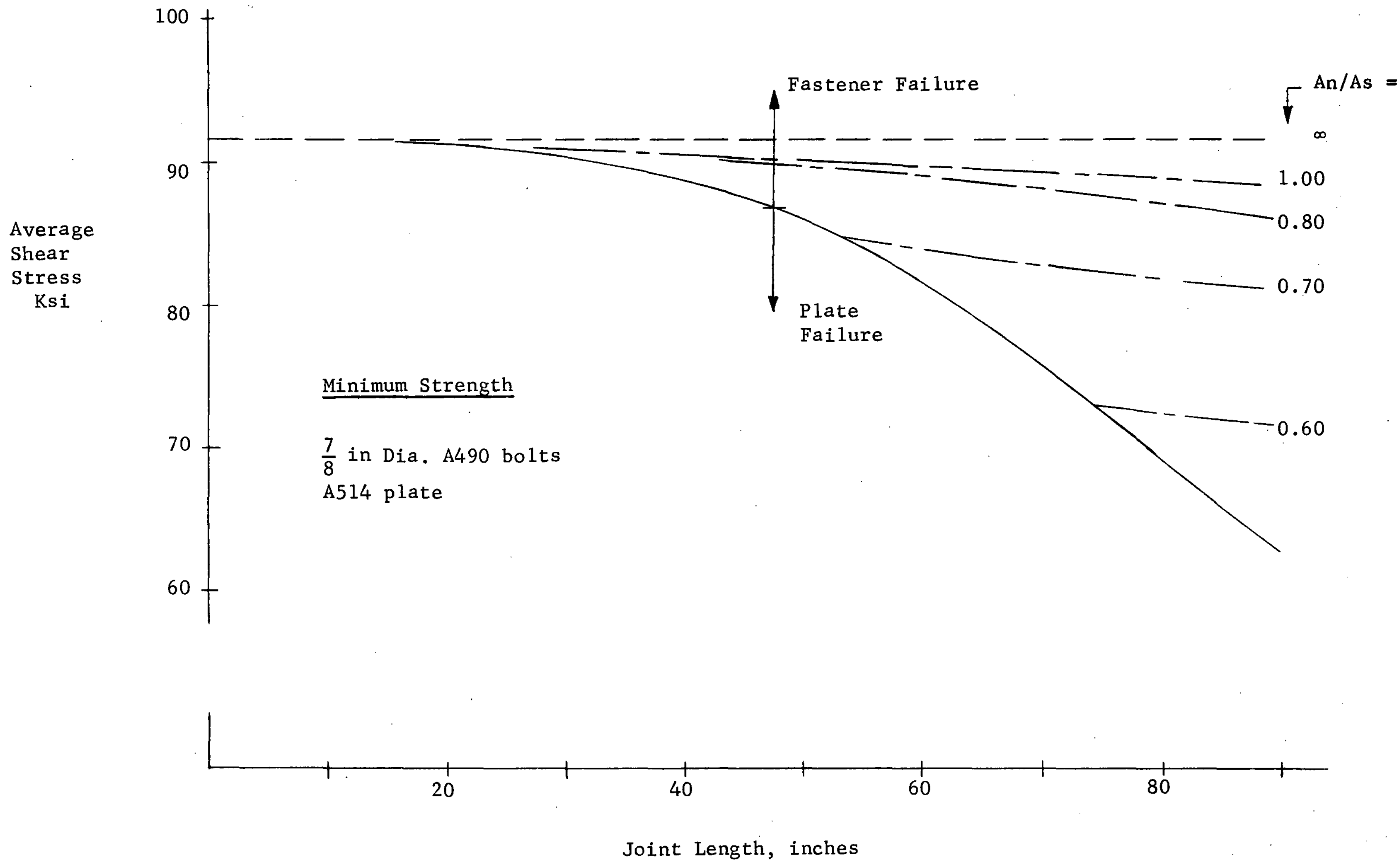


Fig. 2 Plate Failure - Fastener Failure Boundary, τ vs. L.

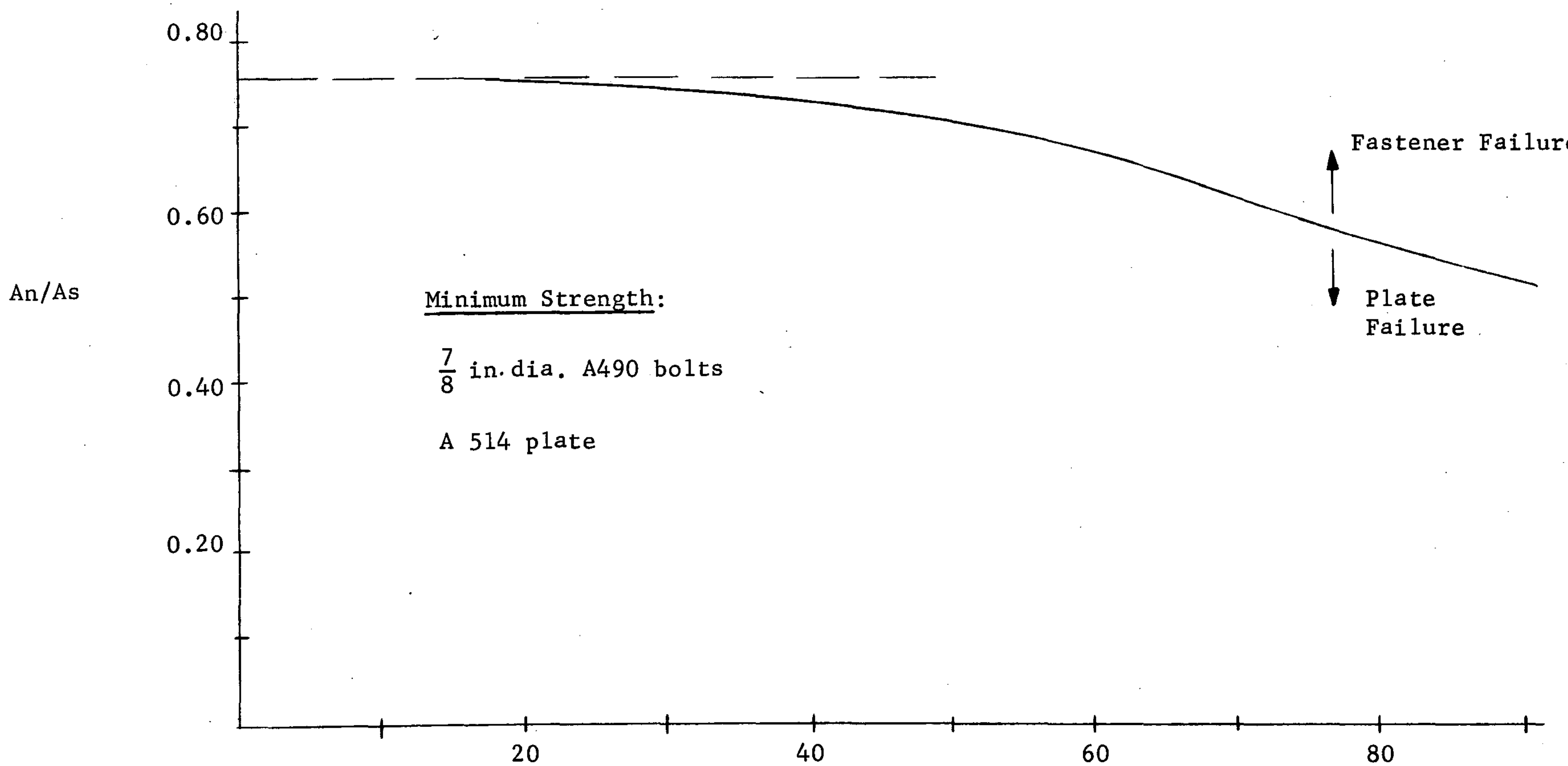


Fig. 3 Plate Failure - Fastener Failure Boundary, An/As vs. L.

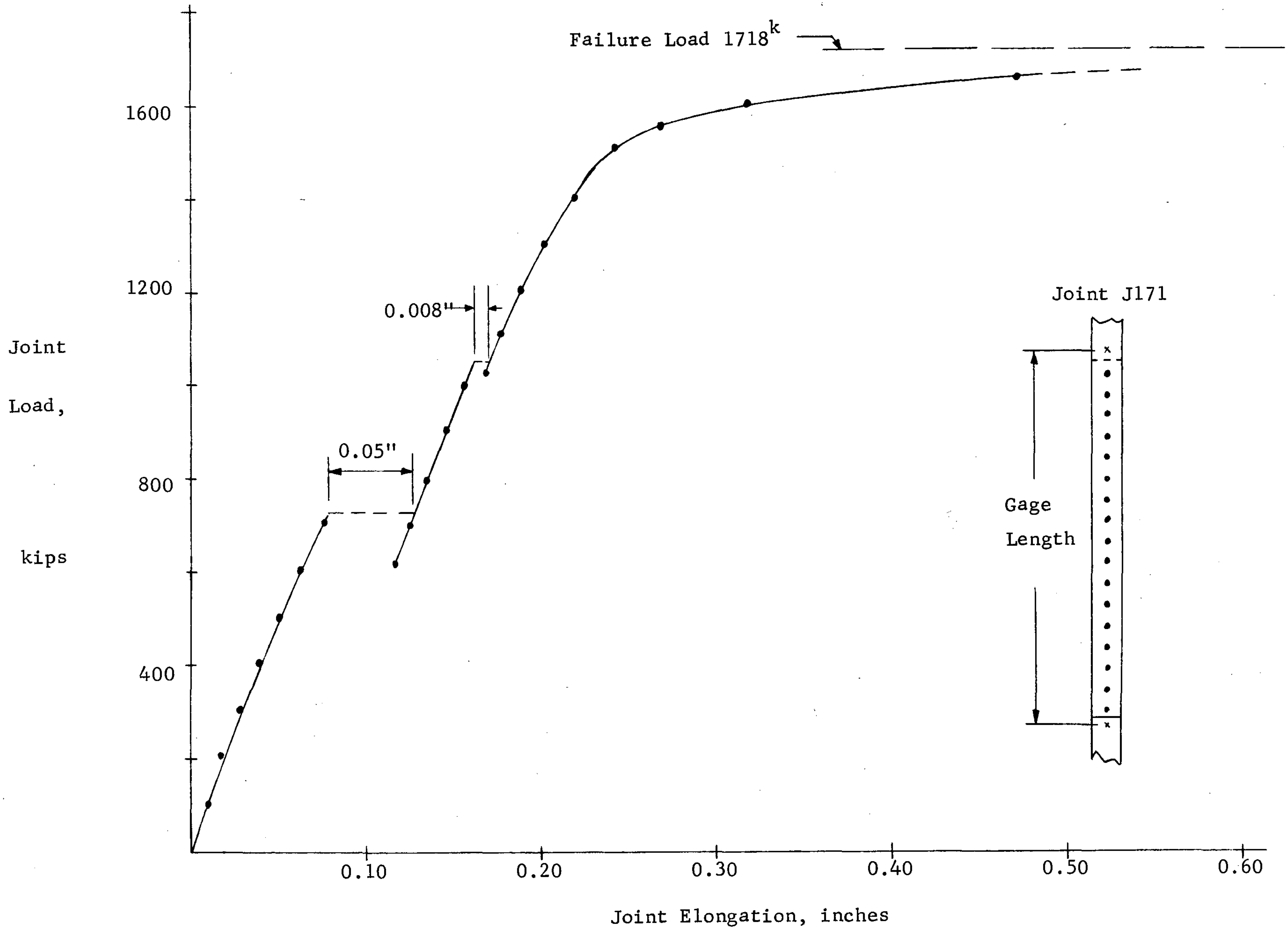


Fig. 4 Typical Load - Deformation Response

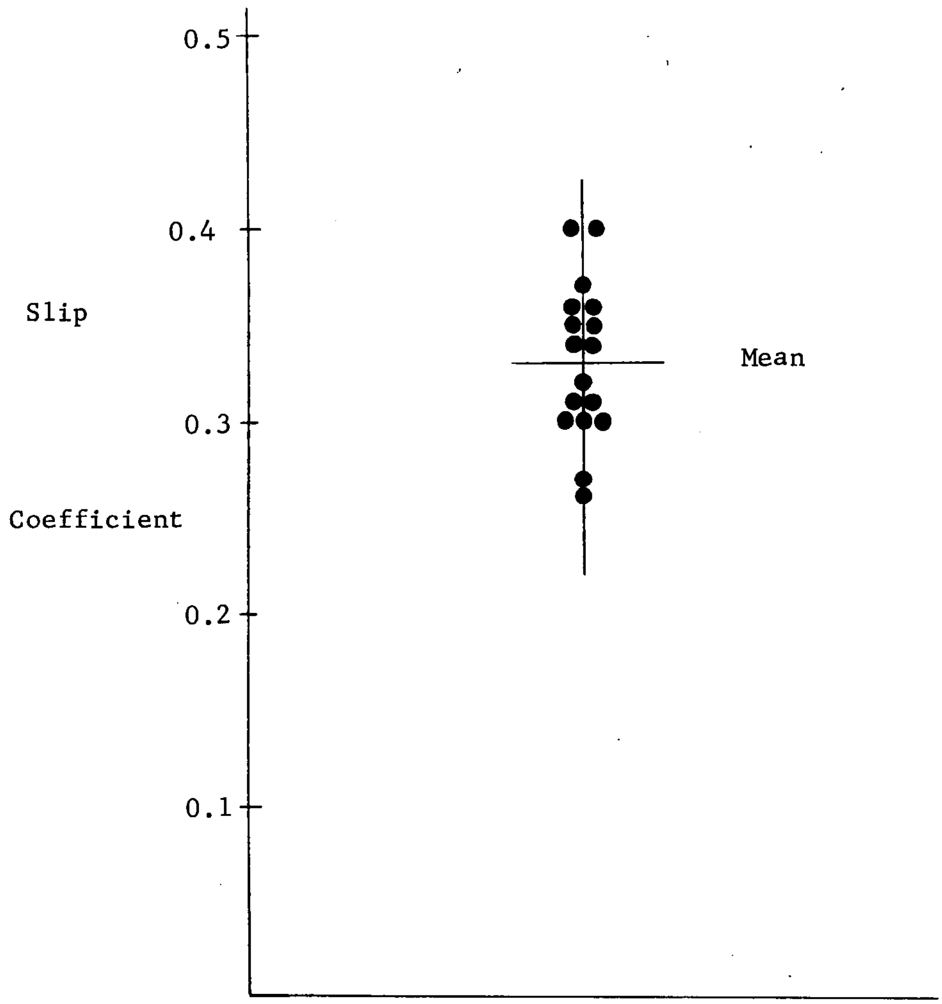


Fig. 5 Slip Coefficient

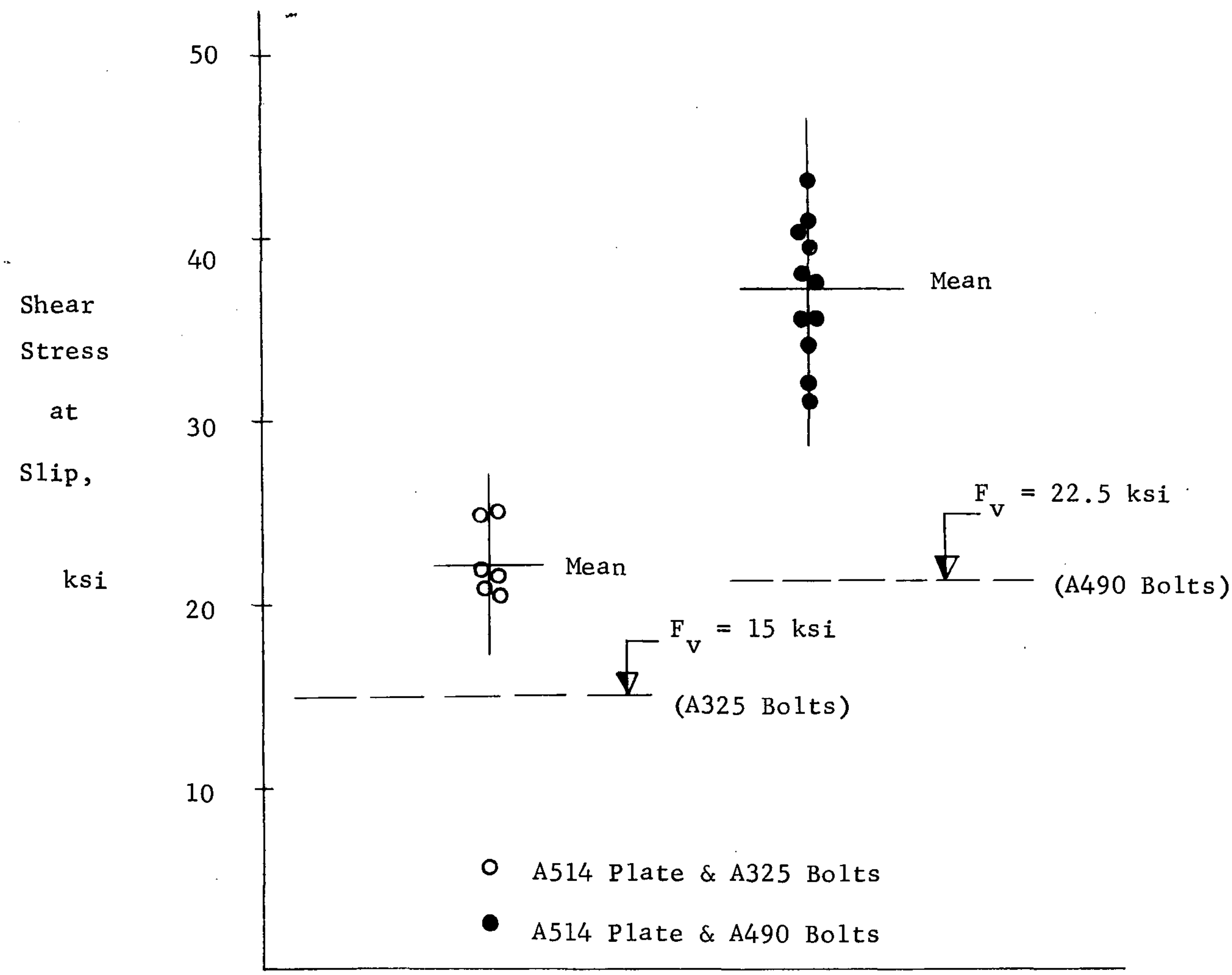


Fig. 6 Slip Resistance